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# Cost Analysis and Air Pollution Impact of Electric Vehicles on a Metropolitan Area.

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# COST ANALYSIS AND AIR POLLUTION IMPACT
# OF
# ELECTRIC VEHICLES ON
# A METROPOLITAN AREA

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## DEDICATION

To the memory of my academic advisor, Dr. Robert McIlhenny,
who was always willing to listen to my ideas and who helped me
to structure my doctoral program.

Thank you for your time and patience.

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## ABSTRACT

During the 1990's, increasing attention has been paid to electric vehicles (EV's) because of their potential to reduce air pollution in metropolitan areas such as the Los Angeles Metropolitan Area in the U.S., Mexico City and Its Metropolitan Area in Mexico, Greater London in the United Kingdom and other urban areas. However, few studies to determine the costs and benefits of reducing air pollution by introducing EV's into these mega cities have been carried out. A model to determine the marginal costs and environmental impact of electric vehicles on a metropolitan area is designed in this study. The model simulates the changes of vehicle characteristics in a transportation system caused by the introduction of EV's. It determines the number of vehicles of each type and their age distribution for every year. Then, the model creates the information required to determine emission factors of hydrocarbons (HC), carbon monoxide (CO), and nitrogen oxides ($NO_x$). The emission factors are determined with MOBILE5, software provided by the U.S. EPA. After these factors are determined, the total emissions caused by the remaining internal combustion vehicles (ICV's) are calculated. The reduction of emissions and the benefits of EV's pollution control programs are estimated. With this model it is possible to determine the reduction of emissions per dollar invested in EV's and the relationship between their costs and benefits. Five scenarios are analyzed. The first three scenarios consider the replacement of ICV's with EV's at different introduction rates. The fourth scenario is the no action taken scenario. The last scenario is one that considers the retirement of the oldest ICV's in the system and replaces these vehicles with new ICV's. Overall, the results indicate that EV's pollution control programs are expensive but effective over the long term when compared to the replacement of old ICV's with new ICV's and other pollution control alternatives.

# CHAPTER 1

# INTRODUCTION

## 1.1 Overview

Mexico City is one of the most polluted cities in the world. International and national permissible levels of pollution are frequently exceeded. As a result, social problems have arisen and become significant and complex. Mexican citizens and authorities are concerned with the effects of air pollution and the lack of efficient alternatives to alleviate this overwhelming situation. Many measures to reduce air pollution have focused on the transportation sector since it is the main source of air pollution.

This study analyzes the use of electric vehicles (EV's) as an alternative to reduce the air pollution caused by conventional transportation within Mexico City and its Metropolitan Area (MCMA). The main focus of this study is to design a model capable of determining the reduction of air pollution in MCMA per dollar invested in EV's. The results obtained with this model are useful when comparing different transportation alternatives to reduce air pollution in Mexico City and in other cities with similar infrastructure and geographical characteristics.

### 1.1.1 Mexico City

According to a report from the United Nations Environment Program and the World Health Organization (UNEP-WHO), the population of Mexico City was estimated to be 19.37 million in 1990, or more than one-fifth of Mexico's total population (UNEP/WHO 1994). Gayer (1993) states that the Mexico City mayor reported that the annual population growth was estimated to be 2.2%. If this growth rate remains constant, it is estimated that there will be 24.51 million people in Mexico City by the year 2000. The UNEP-WHO (1994) reported that "population densities in the city range from almost 7,000 persons per square kilometer in the center to 500 persons per square kilometer in the outskirts."

In Mexico City and its Metropolitan Area (MCMA) there are more than 30,000 industries and 12,000 service facilities. The US Department of Commerce (USDOC) reported that MCMA contains 26% of the industrial base of the country (USDOC 1995). The UNEP-WHO (1994) found that among these industries, 4,000 generate major atmospheric emissions caused by combustion or transformation processes. However, several sources (USDOC 1995, UNEP/WHO 1994, BNA 1993) have found that the largest source of air pollution is the approximately 3.5 million vehicles--buses, minibuses, taxis, trucks, vans, and private cars-- that circulate every day in MCMA. The USDOC (1995) reported that in the valley of Mexico, "660 tons of solvents and 11.4 million gallons of hydrocarbon fuels are used daily." According to the USDOC (1995) the consumption of these chemicals was reported to be as follows: thermoelectric power plants (7%), residences (11%), industry and services (28%), and transportation (54%). The UNEP-WHO (1994) found that "Motor vehicles are by far the main pollution source, as they burn 40 thousand barrels of diesel fuel and 1 million barrels of leaded gasoline each day." The USDOC (1995) said that according to official sources, the transportation sector generates 76.6% of air pollution, natural sources (wind) 15%, industries and services 4.4%, and the energy sector (including the petroleum industry) 4.0%. The UNEP-WHO (1994) reported that in

Mexico City and its Metropolitan Area, international and national permissible levels of air pollution are frequently exceeded.

The UNEP-WHO (1994) and other sources (GEO 1993, Wilkinson and Hay 1987, NCAQ 1982, Wark and Warner 1982, Horowitz 1982, Halvorsen and Ruby 1981, Krzyczkowski. R., Henneman. S. S., Hudson C. L., Putnam. E. S. and Thiesen D. J., 1975. Stern 1968) reported that, in general, air pollution has an adverse impact in humans, animals, vegetation and materials, causing social problems and economic losses. Humans are not only affected by the direct inhalation of the contaminated air but also indirectly by other exposure routes, such as drinking-water contamination, food contamination, and skin transfer. Several of the most common air pollutants directly affect the respiratory and cardiovascular systems. High levels of sulfur dioxide ($SO_2$) and suspended particulate matter (SPM) are associated with increased mortality, morbidity, and impaired pulmonary function. Nitrogen dioxide ($NO_2$) and ozone affect the respiratory system; acute exposure to these pollutants may cause inflammatory and permeability responses, lung function decrements, and increases in airway reactivity. Ozone can cause headaches, and irritate the eyes, nose and throat. Carbon monoxide ($CO_2$) can cause cardiovascular and neurobehavioral effects. Lead impairs liver and kidney function, and causes neurological damage. (In Chapter 2, the characteristics, sources, and effects of these air pollutants are discussed in more detail).

### 1.1.2 Electric Vehicles

The electric vehicle is not a new means of transportation. The first efforts to drive a vehicle by an electric motor were made around 1840. However, not until around 1860, when the lead-acid battery was invented. could electric vehicles be used in practice (Ojerfos and Moren 1983). During the first 20 years of this century, electric vehicles were relatively common for many types of transportation such as taxis, goods delivery vehicles, and public light maintenance vehicles. At the turn of the century when internal combustion vehicles (ICV's) were a new invention. electric vehicles (EV's) outnumbered gasoline-powered vehicles (Sperling 1995). EV's were attractive because of the ease which they could be started and driven. Sperling (1995) found that EV's appeared to be the most popular form of automobile for women. EV's were very popular and sold reasonably well until 1918 (Chan 1993). The use of EV's diminished drastically as the gasoline powered combustion engine (CE) was improved. Around 1910, "the Ford Model T was... selling for less than half of the price of any advertised electric car.... By 1915, less than 2 percent of the 2.5 million [vehicles] in operation in the United States were powered by electricity.... The electric vehicle industry dwindled away, with the last factory in the United States closing in 1935." (Sperling 1995). The number of EV's in the market was reduced to nearly zero because EV's were more expensive and slower than ICV's (Sperling 1995, Chan 1993, Ojerfos and Moren 1983).

Globally, ICV's powered by gasoline invaded the market of private and public transportation within urban areas. ICV's were ahead of the competition as a result of technological innovation. The electric starter replaced the hand crank. engines became more efficient, rubber engine mounts reduced vibrations, and advances in carburetors and ignition made gasoline cars easier to drive (Sperling 1995). As a result, the only EV's that continued in the market were small vehicles that operated at short ranges such as forklifts.

After the invention of semiconductors in the 1950's and continuing improvement in motors and controllers, researchers and manufacturers became interested in electric vehicles again. After the 1960's, small companies and large corporations such as Ford and General Motors started building electric cars and small trucks. In the mid-1970's a number of EV's were introduced to the market again. The acceptance of these EV's was not favorable since the vehicles were not well designed or engineered. Sperling (1995) pointed out that after these adverse results the production of EV's was reduced significantly.

In the late 1970's, the U.S. government introduced major battery R&D projects to assist industry in the development and commercialization of electric vehicles. Henriksen, Hammel, and Altemos (1994) indicated that the government's efforts were initiated to relieve U.S. dependence on foreign oil, following the 1973 oil crisis. Moreover, in the 1980's, concern about deteriorating air quality in many urban areas caused policy-makers to consider mandating the introduction of zero, ultra-low, or low emission vehicles. In 1990, California adopted the Zero Emission Vehicle mandate which requires major automobile manufacturers to start marketing, in 1998, zero emission vehicles (ZEVs) at the rate of 2% of the total car market of each company in California. This percentage increases to 5% in 2001 and 2002, and 10% in 2003 and beyond (Sperling 1995, Henriksen et al. 1994, Wenger and Chang 1994, Chan 1993, Terpstra 1993). Henriksen et al. (1994) reported that several states along the East coast are in the process of enacting similar legislation.

After the ZEV mandate in California was enacted, major investments in electric vehicles were made, resulting in meaningful changes in the EV's technology. Chan (1993) observed that many manufacturers have launched aggressive programs to develop EV's for commercialization; power utilities have launched infrastructure programs for EV's; and government agencies, academic institutions, and related industries have conducted intense R&D to keep improving EV's. So far, many companies such as Ford, GM, Toyota, Nissan, and small manufacturers have developed their own versions of commercial EV's. The ZEV mandate has initiated a major development effort on electric vehicles worldwide, including Europe. In France and Germany, two large fleet trials are in operation (Sporckmann 1994). Many auto makers around the world are preparing to compete commercially and technologically to gain the best market share of EV's in the near future. (In Chapter 2, characteristics of EV's from different companies are described).

#### 1.1.2.1 Environmental Advantages

In general, the significant factors which influenced the revival of EV's were energy cost, energy independence, and environmental protection. However, the major reason for the recent interest in EV's is that electricity is environmentally superior to gasoline (Chan 1993). Sperling (1995), Wenger and Chang (1994), Chan (1993), Terpstra (1993) and many others agree that EV's can dramatically reduce air pollution in congested urban areas. They believe that EV's are the most promising and practical solution to the present problems of air pollution in urban areas since ICV's powered by gasoline and diesel emit the vast majority of human-produced carbon monoxide, about half the hydrocarbon and nitrogen oxide pollutants, and a small proportion of particulate matter and sulfur dioxide.

EV's produce no exhaust, and even those which receive their battery power from fuel electric power plants still allow a significant reduction in total air pollution. This is because electric utilities are far more efficient at producing power than ICV's (Terpstra 1993). Riezenman (1992) indicated two main reasons for the reduction of air pollution by replacing ICV's with EV's based on a study carried out by the Electric Power Research Institute (EPRI) in Palo Alto, California. First, a meaningful amount of electricity comes from non-air-polluting sources like nuclear reactors and hydroelectric plants whereas conventional transportation is powered almost entirely by petroleum products. Second, electric power plants burn fossil fuels much more cleanly and efficiently than ICV's do. These plants are also easier to keep in proper tune, being large, stationary installations whose locations are known, and whose emissions are easily monitored and corrected. In contrast, these measures cannot be easily applied on the millions of ICV's on the road.

Sperling (1995) pointed out that "regardless of the type of power plant, fuel and emission controls, battery powered EV's would practically eliminate emissions of carbon monoxide and hydrocarbon... and would greatly diminish nitrogen dioxide." The California Air Recourse Board (ARB) reported that the existing ZEV mandate could result in ozone-forming pollutant emission reductions, which could meet or exceed a 10% reduction by 2010 and beyond (Wenger et al. 1994). Many other studies have found that EV's reduce air pollution in urban areas. However, the amount of reduction also depends on particular characteristics of each region such as the type of electric power sources, topography, meteorology, etc.

#### 1.1.2.2 EV's Disadvantages

EV's appear to be an important alternative to reduce pollution in urban areas. However, there are three main factors that put EV's at a disadvantage from conventional vehicles.

First. EV's cannot travel long distances with a single charge of battery as ICV's can travel with a tank of gasoline. Second, recharging an EV's battery takes longer than filling a gas tank. Third, EV's are more expensive than ICV's (Riezenman 1992). (Technical details and current prices of EV's are discussed in Chapter 2).

In general. researchers are aware of EV's disadvantages. Nevertheless. many of them (Sperling 1995, Baba, Ishitani and Matsuhashi 1994, Hayashi. Ibi. and Fujioka 1994. Morrow and Dekoster 1994, Prakash, Kirshenbaltt, Hendren, McGonegal, Adams and McLean 1994. Tenure 1994, Sporkmann 1994, Wenger et al. 1994, Chan 1993, Terpstra 1993. Ojerfos et al.1983) agree that the prices of EV's will be reduced and their performance will be improved by investing more in R&D for EV's. Compared with the billions of dollars spent on R&D for ICV's, little money has been spent on EV's development. Sperling (1995) found that during the first years of the 1990's, the total U.S. investment in EV's and batteries by industry and government was probably less than $1 billion. Tenure (1994) and others have indicated that initially it will be difficult to sell EV's as it is for most new products; however, they believe that as more and more people buy EV's, more money will be available for R&D. Moreover, after selling the new EV's. customer feedback will undoubtedly be used to improve these vehicles.

### 1.2 Problem Definition

The fundamental problem being addressed is the high level of air pollution that is continuously threatening the well being of Mexico City and its Metropolitan Area. The unacceptable levels of air pollution in MCMA have forced the Mexican government and its citizens to consider alternatives to lessen air pollution. Since the largest source of air pollution is the transportation system (BNA 1993, UNEP/WHO 1994, USDOC 1995), measures within this sector have been taken into consideration; for instance, a program to reduce the number of vehicles circulating per day was created in 1989, lead-free gasoline was introduced in 1990, car emission inspections were also enforced in 1990, catalytic convertors were required for new cars after 1991, and commercial vehicles are being converted from gasoline to alternative gas combustion (USDOC 1995, Parkinson 1993). However, significant reduction in air pollution has not been experienced after the implementation of the above mentioned alternatives (USDOC 1995, Baker and van Aardenne 1993, UNEP-WHO 1994). (The reasons these alternatives have not been effective in reducing pollution to desirable levels are discussed in section 2.2.3). As a result, MCMA is still demanding environmentally and economically efficient alternatives to develop a cleaner transportation system.

Other alternatives to reduce air pollution caused by conventional vehicles have been suggested, namely, the use of electric powered vehicles, hybrid vehicles, and alternative fuels such as reformulated gasoline, methanol from natural gas, alcohol fuels from biomass, and natural gas (Sperling 1995, Strauss and Mainwaring 1984). Eskeland (1992) suggests that "if policy makers want to evaluate the various ways of making vehicles and fuels cleaner, they will need to know the economics of vehicle modification; that is, what yields the most emissions reduction per dollar?" In order to answer this question, characteristics of each alternative have to be studied considering the particular conditions of MCMA that influence the concentration of air pollutants and traffic patterns such as type of natural resources. electric power sources (natural gas), topography, climate, demography. and cultural aspects.

The transportation alternative that is analyzed in this research is the use of electric powered vehicles. Although several studies to determine the environmental impact of EV's have been carried out (Baba et al. 1994. Hayashi et al. 1994. Morrow et al. 1994. Prakash et al. 1994. Tenure 1994. Sporkmann 1994, Wenger et al. 1994), the methodology and results are different in each study since these studies have been made for particular regions, considering specific constraints. For instance, all the above mentioned authors did their research for specific cities within technologically and economically powerful countries such as United States. Japan, Germany, and Canada. The constraints and assumptions differ from study to study and these will be analyzed in Chapter 2. Moreover, when the environmental impact of EV's has been studied, researchers have focused on purely environmental aspects, giving slight consideration to the economic issues; on the other hand. when the economic implications of EV's have been thoroughly analyzed. environmental aspects are only superficially considered. Hence, a study that considers the relationship between costs and environmental effects of EV's on MCMA while comparing them with the effects of conventional transportation will be useful. Thus, this study addresses the following question:

- How many EV's are required to reduce emissions of air pollutants to desirable levels and what is the relationship between the cost and the reduction of these emissions? i.e., what is the reduction of emissions in MCMA per dollar invested in EV's?

## 1.3 Objectives

The objective is to study the relationship between costs and environmental effects of EV's and to compare these effects with the effects of the current internal combustion vehicles in MCMA are listed as follows:

- Select the electric vehicles that are best suited to the traffic patterns, topography, and climate of MCMA were selected.
- Compare the cost and environmental performance of the EV's with compared to the total cost and performance of ICVs in MCMA.
- Determine and compare the environmental impact of EV's on MCMA with the current effects of ICV's on the environment.
- Determine the number of EV's required to reduce emission levels of air pollutants to desirable levels and the relationship between the costs incurred and the reduction of emissions.
- Develop program schedules for introducing EV's to MCMA, assuming that governmental mandates such as the Zero Emission Vehicle (ZEV) law from California are implemented.

# CHAPTER 2

# LITERATURE REVIEW

This chapter is divided it into four main sections: Air Pollution, Mexico City and its Air, Electric Vehicles, and Environmental and Economic Studies of EV's. Section 2.1 (Air Pollution), provides basic definitions of air pollution and related concepts: air pollutants characteristics, sources, and their effects; and economic issues associated with benefits of control programs and losses caused by air pollution are presented. In Section 2.2 (Mexico City and its Air), demographic and air pollution information about Mexico City and its Metropolitan Area (MCMA) is given. The main measures that have been implemented in MCMA in order to reduce air pollution problems caused mainly by gasoline-powered vehicles are discussed. This section concludes by addressing MCMA economic issues associated with air pollution. Within Section 2.3 (Electric Vehicles), technical data on EV's such as car performance and battery characteristics are presented. Also, information about market prices of EV's is given in this section. Finally, in Section 2.4 (Environmental and Economic Studies of EV's), methodology and results from environmental and economic analysis associated with EV's are discussed.

## 2.1 Air Pollution

Air pollution is a global problem. Major metropolitan areas around the world such as the Los Angeles Metropolitan Area and the New York City Metropolitan Area in the United States: the Metropolitan Area of Mexico City in Mexico; the Calcutta Metropolitan District, Delhi, and Greater Bombay in India; Beijing Municipality and Metropolitan Shanghai in

China; Greater Cairo in Egypt; Metropolitan Bangkok in Thailand; Karachi in Pakistan; Greater London in the United Kingdom; and other smaller cities are suffering from the adverse effects of air pollutants on humans, animals, vegetation, and materials (Sperling 1995, UNEP-WHO 1994, Sinha 1993, Strauss and Mainwaring 1984, Luke 1982, Stern 1968). In general, if major corrective and preventive measures are not implemented, researchers expect that the number of cities experiencing air pollution will increase and the effects of pollution will seriously affect people and their habitat (UNEP-WHO 1995, Strauss and Mainwaring 1984). The seriousness of the problems varies depending mainly on the following factors: air pollution sources, type of pollutants, climate, meteorology, topography, demography, level of industrialization and socioeconomic development. (UNEP-WHO 1994, Strauss and Mainwaring 1984, Cohn and McVoy 1982, Stern 1968).

### 2.1.1 Definitions

**Air Pollution.** There is no standard definition of air pollution. Scientists and engineers define air pollution differently. For instance, from the scientists' standpoint, the words 'air pollution' imply an assumption of some sort of atmospheric norm from which variance can be observed (Stern 1968). From the engineering standpoint, "air pollution is the waste remaining from the ways we produce our goods, transport ourselves and our goods, and generate the energy to heat and light the places where we live, play and work" (Wark and Warner 1982). For this study, air pollution will be defined as the alteration of the normal concentration of the air constituents caused by human and natural activities.

Generally, the normal concentration of the air constituents refers to the concentration of air constituents in dry atmospheric air at surface level. The normal air constituents and their concentrations are shown in Table 2.1.

**Air pollutants.** It is common practice to consider as pollutants only those substances added in sufficient concentration to produce a measurable effect on humans, animals, vegetation, or material. Therefore, pollutants may be almost any natural or artificial composition of matter carried by or through the air. They may exist as solid particles, liquid droplets, or gases, or various mixtures of these forms. Pollutants may be a single chemical or a very large number of kinds and sizes of substances (Stern 1968). Generally, air pollutants are classified as follows: particulate matter, sulfur compounds, organic compounds, nitrogen compounds, carbon compounds, halogen compounds, and radioactive compounds (Stern 1968, Wark and Warner 1982). Specifically, the most common pollutants in urban areas are sulphur dioxide ($SO_2$), nitrogen oxides (NO and $NO_2$) (collectively represented as $NO_x$), carbon monoxide (CO), hydrocarbons (HC), ozone ($O_3$), suspended particulate matter (SPM), and lead (UNEP-WHO 1994, Ball, Hamilton, and Harrison 1991, Strauss and Mainwaring 1984, Horowitz 1982, Wark and Warner 1982, Cohn and McVoy 1982, Sharp and Jennings 1976).

**Concentration.** Concentration is the amount of air components (constituents and/or pollutants) per cubic meter. It is also defined as parts of air components per million parts of air. For example, it is common to express the quantity of gaseous components in the air as part per million (ppm):

Table 2.1 Normal Air Constituents and Their Concentrations.
( Wark and Warner 1982, pg. 6).

| Substance | Volume (percent) | Concentration (ppm) |
|---|---|---|
| Nitrogen | 78.084 ± 0.004 | 780,900 |
| Oxygen | 20.946 ± 0.002 | 209,400 |
| Argon | 0.934 ± 0.001 | 9,300 |
| Carbon dioxide | 0.033 ± 0.001 | 315 |
| Neon | | 18 |
| Helium | | 5.2 |
| Methane | | 1.2 |
| Krypton | | 0.5 |
| Hydrogen | | 0.5 |
| Xenon | | 0.08 |
| Nitrogen dioxide | | 0.02 |
| Ozone | | 0.01-0.04 |

1 volume of gaseous component / $10^6$ volumes (component + air) = 1 ppm

0.0001 percent of volume = 1 ppm.

The mass of an air component is expressed as micrograms of component per cubic meter of air. It is represented as follows at STP (P=1 atm, T=25° C):

micrograms/cubic meter = $\mu g/m^3$ = (40.81) (ppm) (molecular weight)

**Emission.** This term refers to the flow of polluting substances into the air: that is, the injection of materials into the atmosphere at certain rates. It is measured in flow units, such as the mass of pollutant emitted per unit of time or per unit of human activity (Horowitz 1982).

**Permissible Limits.** International, national and local authorities around the world have defined acceptable levels of air pollutant concentrations in the atmosphere. These levels of pollutant concentrations are based mainly on their effects on human health. The maximum concentration of a specific pollutant that many healthy human beings can be exposed to, day after day, without suffering negative effects, is defined as the permissible limit of that specific pollutant (Olishifski 1988). The permissible limits are used to regulate the emission from different sources of air pollution. These limits may vary from country to country and also within a country (UNEP-WHO 1994). Table 2.2 shows a summary of the World Health Organization (WHO) air quality permissible limits of exposure.

### 2.1.2 Characteristics, Sources and Effects of Air Pollutants

This section describes the physical characteristics, sources, and effects of common air pollutants in urban areas. Figure 2.1 shows the major sources of air pollution in a mega

Table 2.2 Summary of Air Quality Guidelines of the World Health Organization. (UNEP/WHO 1994, pg. 12)

| Pollutant | Time-weighted average | Units[a] | Averaging time |
|---|---|---|---|
| Sulfur dioxide | 500 | µg/m$^3$ | 10 minutes |
| | 350 | | 1 hour |
| | 100-150[b] | | 24 hours |
| | 40-60[b] | | 1 year |
| Carbon monoxide | 30 | mg/m$^3$ | 1 hour |
| | 10 | | 8 hour |
| Nitrogen dioxide | 400 | µg/m$^3$ | 1 hours |
| | 150 | | 24 hour |
| Ozone | 150-200 | µg/m$^3$ | 1 hour |
| | 100-120 | | 8 hours |
| Suspended particulate matter | | | |
| Black smoke | 100-150[b] | µg/m$^3$ | 24 hours |
| | 40-60[b] | | 1 year |
| Total suspended particulates | 150-230[b] | | 24 hours |
| | 60-90[b] | | 1 year |
| Thoracic particles ($PM_{10}$)[c] | 70[b] | | 24 hours |
| Lead | 0.5-1 | µg/m$^3$ | 1 year |

[a] Micrograms per cubic meter of air (µg/m$^3$); milligrams per cubic meter of air (mg/m$^3$).
[b] Guideline values for combined exposure to sulfur dioxide and suspended particulate matter (they may not apply to situations where only one of the components is present).
[c] Particles of less than 10 µm in diameter.

city. Los Angeles. It is noted that in this metropolitan area the major source of pollution is the transportation sector, as it is in Mexico City.

**2.1.2.1 <u>Sulfur Dioxide</u> ($SO_2$)**

**Physical Form.** Sulfur dioxide is a colorless, irritating gas. It readily combines with water to become sulfurous acid. Either in water on in the air. it can be oxidized easily to sulfuric acid or sulfates. Although technically incorrect. the term sulfate is used to include the sulfurous-acid and sulfite forms. Sulfate may occur as droplets or dry particles (Halvorsen and Ruby 1981).

**Main Sources.** Combustion of fossil fuels in stationary sources such as electric power plants and primary metals industries is the major source of $SO_2$ in most large cities. Another significant generator of $SO_2$ is the combustion in industrial boilers and manufacturing processes. Residential combustion of solid fuels, mainly coal and wood, also represent an important source of $SO_2$ in some cities. particularly those in the developing countries. Diesel-fueled engines are significant contributors of $SO_2$. as well. Finally. the last contributors are natural sources such as forest fires (UNEP-WHO 1994, Wark and Warner 1982, Strauss and Mainwaring 1984, Halvorsen and Ruby 1981, Stern 1962).

**Effects.** Exposures to sulfur dioxide of less than one hour at concentrations of 0.75-1 ppm have produced changes in lung functioning in healthy young men and substantial changes among active youths with asthma. People over 55 years of age with chronic bronchitis and emphysema are believed to be the group most vulnerable to $SO_2$.

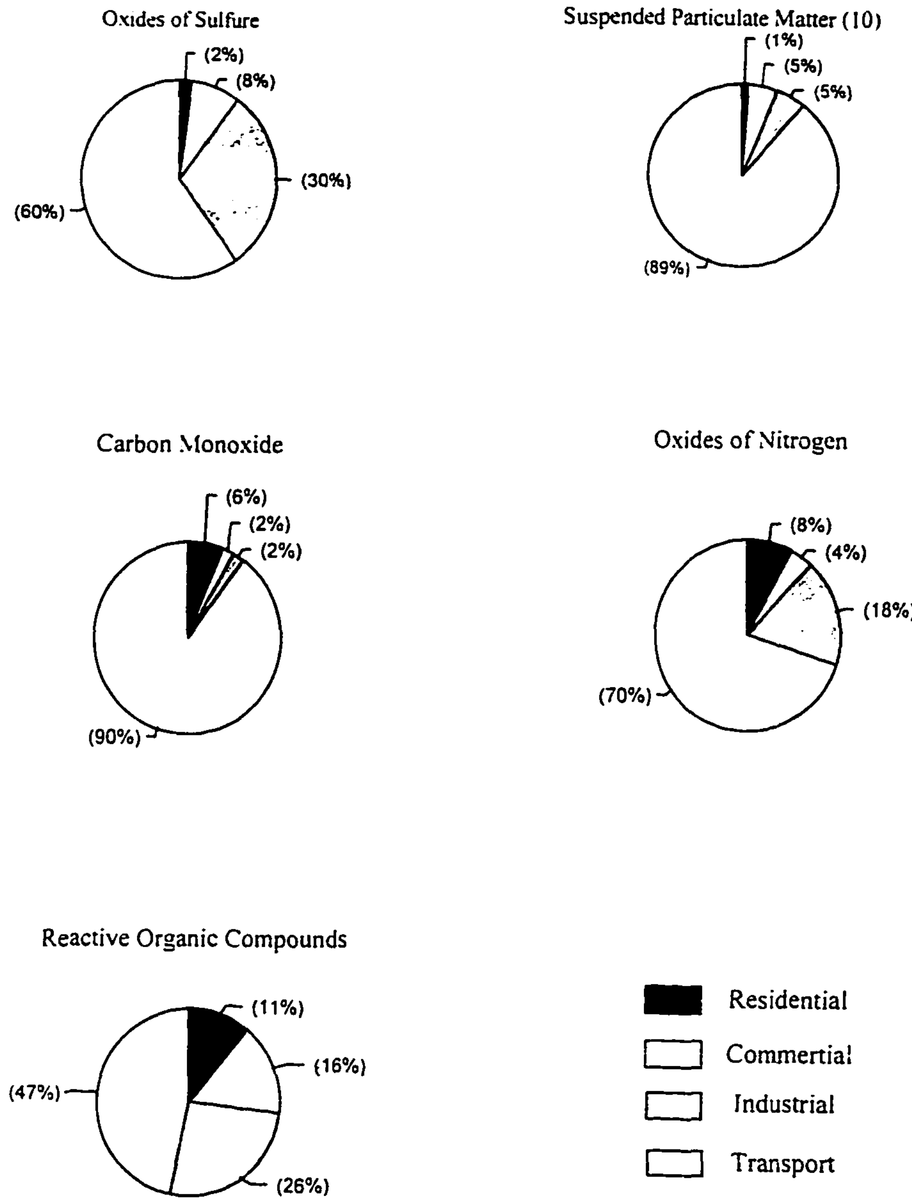


Figure 2.1 Major Sources of Air Pollution in a Mega City. (South Coast Air Quality Managament District. Air Quality Management Plan: South Coast Air Basin. Los Angeles: Southern California Association of Governments, 1991).

In regions with high concentrations of $SO_2$ (around 700 $\mu g/m^3$), in the presence of particulate matter, there are observable effects on health, such as increased mortality and morbidity of the aged and infirm (UNEP-WHO 1994, Halvorsen and Ruby 1981). Numerous animal species, including humans, respond to sulfur dioxide by bronchoconstriction, which may account for a slight increase in airway resistance (Wark and Warner 1982).

Sulfur dioxide in the atmosphere increases the acidity of rainfalls, which causes the increased acidity in lakes and streams. As a result, entire biologic communities of plants, small food animals, and fish have disappeared from whole lakes and river systems. Alfalfa, pasture grasses, wheat, and other crops have been affected from exposure to $SO_2$. A number of trees such as larch, pine, birch, and Douglas fir, are also susceptible to $SO_2$ (Halvorsen and Ruby 1981).

Sulfurous or sulfuric acids are also capable of attacking a wide variety of building materials including limestone, marble, roofing slate, and mortar. Oil-based paint is also harmed by $SO_2$. Where humidity is high, $SO_2$ can damage steel and other metals. Textiles of nylon are also susceptible to $SO_2$ (Wark and Warner 1982, Halvorsen and Ruby 1981).

**2.1.2.2 <u>Nitrogen Oxides</u> ($NO_x$)**

**Physical Form.** Nitric oxide is an odorless, colorless gas. Nitrogen dioxide is a yellow-brown gas with a sweet, pungent odor. Both can oxidized in the air to nitrates, which may be present in either gaseous or particulate form. Although technically incorrect, the term nitrate is used to include the nitrous-acid and nitrate forms. Nitrogen oxides also can react with simple amine molecules to form nitrosamine (Halvorsen and Ruby 1981).

**Main Sources.** The major sources of nitrogen oxides are motor vehicles and stationary combustion sources, such as coal- or oil-fired power plants and industrial boilers. In most of the studies, it has been found that the transportation sector accounts for the largest percentage of $NO_x$ generation (UNEP-WHO 1994, Wilkinson and Hay 1987, Wark and Warner 1982, Halvorsen and Ruby 1981, Horowitz 1982). Natural sources are important generators since these may exceed half of the total emission. Significant indoor sources of nitrogen dioxide are gas cooking stoves (Halvorsen and Ruby 1981).

**Effects.** Nitrogen oxides can react chemically in the air to form nitrous and nitric acid, nitrate salts and organic compounds of nitrogen. Because of the acidic products, $NO_x$ are significant contributors of acid rain. Nitrogen dioxide is a pulmonary irritant, and short exposures to it may increase susceptibility to acute respiratory diseases. It was found that children living near large stationary source of nitrogen dioxide with annual average levels above 0.08 ppm experienced higher rates of bronchitis and other respiratory problems. Aggravation of heart- and lung-disease symptoms have been observed among elderly patients when nitrate concentrations are over 4 $\mu g/m^3$. Studies have also found that inhalation of nitrosomes causes cancer in animals and is presumed to be carcinogenic in humans.

$NO_2$ is harmful to plants at high concentrations; however, most plants are not harmed by $NO_2$ at the concentrations that usually occur in the atmosphere. At a concentration of 0.5 ppm for a period of 10 to 12 days, $NO_2$ has reduced growth of such plants as pinto beans and tomato. Orange trees are apparently the most susceptible; reduced yields are observed from prolonged exposers at 0.25 to 1 ppm.

Nitrogen dioxide can react with moisture to form nitric acid, which can cause significant corrosion of metal surfaces. In addition, visible light is absorbed by the $NO_2$, which at a concentration of 0.25 ppm will cause appreciable reduction in visibility. Photochemical smog is formed by the reaction of $NO_x$ with unburned hydrocarbons in the presence of sunlight. (UNEP-WHO 1994, Wilkinson and Hay 1987, Wark and Warner 1982, Halvorsen and Ruby 1981, Horowitz 1982).

**2.1.2.3 Carbon Monoxide (CO)**

**Physical Form.** Carbon monoxide is colorless and odorless. It is very stable and has a lifetime of 2 to 4 month in the atmosphere (Wark and Warner 1982).

**Main Sources.** The incomplete combustion of carbon-based fuels generates carbon monoxide. Studies reveal that about three-fourths of all carbon monoxide emissions are caused by the operation of internal combustion vehicles. The concentration of CO in the atmosphere is dependent on time of day, location, weather and human activities. CO levels tend to be highest on areas of heavy vehicular traffic. Gas and wood cooking and heating stoves and cigarette smoking are indoor sources of CO (UNEP-WHO 1994, Wilkinson and Hay 1987, Wark and Warner 1982, Halvorsen and Ruby 1981, Horowitz 1982).

**Effects.** CO combines with the hemoglobin of the blood to produce carbon oxyhemoglobin which reduces the ability of the blood to carry oxygen. When concentrations of CO exceed 100 ppm, nausea, headache, weakness, dizziness, and leg pain are common. At high concentrations (>750 ppm), CO is fatal to humans. At the concentrations in urban areas, CO is not fatal, but it can aggravate cardiovascular diseases and may impair psychomotor functions. On the other hand, numerous experiments have not shown serious effects of CO on higher plant life at urban concentrations. CO appears to have no harmful effects on material surfaces (Wilkinson and Hay 1987, Wark and Warner 1982, Halvorsen and Ruby 1981, Horowitz 1982).

2.1.2.4 Hydrocarbons (HC)

**Physical Form.** Hydrocarbon data are generally presented as total hydrocarbon, specific or speciated hydrocarbons, or volatile organic compounds (VOCs). VOCs are non-methane hydrocarbons and other organic compounds including oxygenated and halogenated organics (Ball, Hamilton, and Harrison 1991). For practical purposes, studies of air pollution refer to all non-methane hydrocarbons (NMHC) as hydrocarbons (HC), reactive organic gas (ROG), or volatile organic compounds (VOCs) (Wenger 1994, Prakash, Kirshenbaltt, Hendren, McGonegal, Adams and McLean 1994, Sporckmann 1994, UNEP-WHO 1994, Ball, Hamilton, and Harrison 1991).

**Main Sources.** Gasoline- and diesel-powered transportation vehicles and various petroleum operations are the major sources of people-made hydrocarbons emissions. These emissions are similar to carbon monoxide emissions in that internal combustion vehicles are the primary source. Hydrocarbons can also be emitted by stationary source fuel combustion, chemical processing, and petroleum refining, storage and distribution (UNEP-WHO 1994, Wilkinson and Hay 1987, Wark and Warner 1982).

**Effects.** Many studies have demonstrated that gaseous hydrocarbons do not have direct adverse impact on human health. However, some hydrocarbons react in sunlight with other air pollutants to form smog which can irritate the nose and eyes, reduce visibility, reduce lung function and aggravate respiratory diseases. Of all the hydrocarbons, only ethylene has negative effects on plants at urban ambient concentrations; the main effect of ethylene is to inhibit plant growth. The importance of hydrocarbons as air pollutants arises mainly from their role in atmospheric chemical reactions that produce nitrogen dioxide and ozone which are harmful at or near atmospheric concentrations (Wilkinson and Hay 1987, Wark and Warner 1982, Horowitz 1982).

**2.1.2.5 Ozone ($O_3$)**

**Physical Form.** It is a colorless gas with a sharp smell (Halvorsen and Ruby 1981).

**Main Sources.** Ozone is a major transportation-related pollutant. However, it does not have significant direct emissions sources; $O_3$ is a secondary pollutant that is formed in the air by photochemical reactions involving HC and $NO_x$. The resulting mixture of pollutants generally is named photochemical smog. In addition, the reactions of HC and $NO_x$ that form ozone also oxidize NO and produce small quantities of other inorganic and organic compounds, such as nitric acid and peroxyacetylnitrate (PAN). Ozone also occurs naturally in the stratosphere and may be brought down to lower elevations under certain weather conditions, particularly at the end of the winter and beginning of spring in northern latitudes (Horowitz 1982, Halvorsen and Ruby 1981).

**Effects.** Ozone is a pulmonary irritant that causes significant discomfort, symptoms of respiratory illness, and reduced pulmonary function in sensitive individuals. It directly attacks cells, paralyzes cilia, increases secretion of mucus, and can disable portions of the lung at moderate concentrations. Ozone is also toxic to plants and damages many materials. Spinach, pinto beans, tomatoes, aspen, ash and azaleas are among the more sensitive plants. Yield reduction in root crops have been reported from short-term exposures to $O_3$ concentrations of 0.25 ppm. Chronic exposures of 0.05 ppm have been found to cause a yield loss of 50% in alfalfa, a 10% yield loss in corn, and 25-50% yield loss in potatoes. Rubber compounds become brittle when exposed to $O_3$ at 0.05 ppm (Wark and Warner 1982, Horowitz 1982, Halvorsen and Ruby 1981).

**2.1.2.6 Lead**

**Physical Form.** Lead is a heavy metal found as a fine particle or condensed on the surface of other particles (Horowitz 1982, Halvorsen and Ruby 1981).

**Main Sources.** Except around lead smelters and other nonferrous mining and smelting operations, almost all the lead in the atmosphere is produced by motor vehicles burning gasoline containing lead antiknock compounds (UNEP-WHO 1994, Horowitz 1982, Halvorsen and Ruby 1981).

**Effects.** Lead is poisonous to humans. It causes damage to the nervous system and kidneys. Lead particles are deposited either in the throat or in the lung. In infants and children, as much as 50% of the inhaled lead is eventually absorbed into the blood. Indications of damage in normal hemoglobin production are observed in children when blood lead concentration exceed 200 μg/L. Significantly lower mental ability among children with blood lead concentrations above 350-400 μg/L has been found. In an area where air lead concentrations were above 1.5 $\mu g/m^3$, it was reported that 7% of the children had blood lead in excess of 400 μg/L. In areas with soil contaminated by lead air pollution, poisoning of animals which tend to eat roots can be a problem (UNEP-WHO 1994, Horowitz 1982, Halvorsen and Ruby 1981).

**2.1.2.7 <u>Suspended Particulate Matter</u> (SPM)**

**Physical Form.** "Particulate matter may be liquid (droplets) or dry particles from 0.01 μm(micrometers) to 100 μm in diameter (a human hair is about 100 μm in thickness). The greatest number of particles are the 'fine' particles (less than 3 μm). where the most mass is in the 20-20 μm size range. Fine particles may remain suspended in the air for a very long time, but particles larger than 25 μm rapidly fall to the ground" (Halvorsen and Ruby 1981).

**Main Sources.** The major sources of human-made particulate matter are the mineral products, iron and steel, and non-ferrous metals industries. Motor vehicles also produce a significant mass of small particles from combustion exhaust and large particles from roads.

**Effects.** Fine particles (less than 1μm in size) are the most damaging to human health. These can impair lung function and reduce respiratory capabilities. Acidic and alkaline particulate can cause damage to materials. For example, these particles can discolor paint, weaken fabrics, fade textiles and corrode metals, among other effects. Moreover, particles greater than roughly 0.1 μm in size tend to reduce visibility.

**2.1.3 Factors that Affect Air Pollution**

The level of air pollution in urban areas depends on the concentration of pollutants in the air. All air pollutants are transported, dispersed, or concentrated in the atmosphere. The airborne cycle begins with the emission of pollutants, followed by their transport and diffusion through the atmosphere. This cycle is completed when the pollutants are deposited on humans, animals, vegetation, soil and water surfaces, and other objects, when they are washed out of the atmosphere by rain, or when they escape into space (Wark and Warner 1982). The transport, dispersion and concentration of pollutants are affected mainly by meteorological and topographical factors (UNEP-WHO 1994, Strauss and Mainwaring 1984, Wark and Warner 1982, Stern 1968).

Meteorological factors refer to wind structure, temperature, pressure, humidity, sunshine, precipitation, visibility and atmospheric composition. Topographical factors refer to characteristics of terrain, including its relief (land forms), rivers, lakes, etc., and such human-made features as dams, canals, bridges, buildings and roads. The combination of many of these components or a simple component can cause positive or negative impact on the air pollution of a particular region (UNEP-WHO 1994, Strauss and Mainwaring 1984, Wark and Warner 1982, Stern 1968). Details of the interaction between each of these factors and air pollutants are extensively explained in air pollution bibliographies (Strauss and Mainwaring 1984, Wark and Warner 1982, Stern 1968). For the purpose of this research, only common phenomena caused by meteorological and topographical factors in urban areas are considered, namely, thermal inversion, urban heat island, street canyon effect and mountain barriers.

Thermal inversion is a particular problem for cities in temperate and cold climates. Under normal dispersive conditions, hot pollutant gases cool as they rise since they come into contact with colder air masses at high altitudes. However, under certain circumstances, the air temperature remains hot with altitude, and an inversion layer is formed at a few tens to hundreds of meters above the ground. This inversion layer may then trap pollutants near to the emission sources and act as a heat cover, prolonging the inversion. When wind speeds are low these conditions become a great concern. When temperatures remain constant with altitude, a similar effect may be presented (UNEP-WHO 1994, Strauss and Mainwaring 1984, Wark and Warner 1982).

Urban heat islands are another phenomenon that affects the quality of air in large cities. The atmosphere in urban areas differs in many ways from that of the countryside. Houses, buildings, and factories form an irregular surface that retards the free flow of large air masses. In addition, because of the perpendicular building surfaces more solar energy is absorbed during the day and retained for a longer period at night than is in an equal area outside the city. Consequently, the heat generated by a city causes the air to rise, carrying upward the burden of pollution, then expands and flows outward over the edges of the city. As the air moves toward the edges of the city, it cools, and later it flows back toward the center of the city near the ground drawing in colder and possibly more polluted air from surrounding industrial areas (UNEP-WHO 1994, Wark and Warner 1982). (Figure 2.2 illustrates the heat island phenomenon).

The street canyon effect takes place when the dispersion of low-level emissions is prevented due to tall buildings on each side of busy roads. This phenomenon is present on a local scale. Buildings and other structures can have a great effect upon pollution dispersion by preventing air circulation (UNEP-WHO 1994).

The mountain barrier problem is similar to the street canyon phenomenon. The difference is that it occurs on a larger scale. The mountains surrounding urban areas such as in Los Angeles and Mexico City prevent or limit the action of the prevailing regional

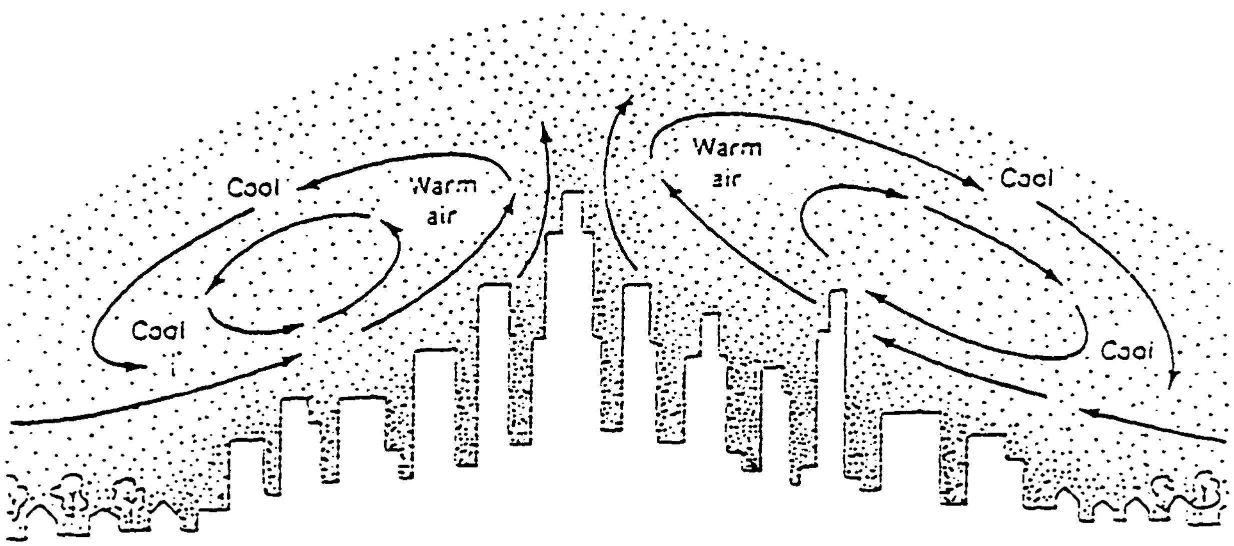


Figure 2.2 Urban Heat Island. (Wark and Warner 1982, pg. 95).

wind. resulting in lower wind speeds at the surface inside the cities than outside. As a result. little exchange of air between a valley and the outside may occur over long periods (Stern 1968). The UNEP-WHO (1994) say that hills surrounding a city often act as a downwind barrier, trapping pollution close to the city. These organizations also reported that "when cities are surrounded by high mountains. like Los Angeles and Mexico City. the pollutants may be trapped within the airshed for several days."

### 2.1.4 Economic Issues

The economic aspects considered in evaluating air pollution control programs are the economic losses due to air pollution, the cost of the programs and the monetary benefits of these programs. From an economic standpoint, a cost-benefit analysis (CBA) evaluates the cost of a control program versus the economic benefits that this program offers or the economic losses that can be avoided.

Generally, a CBA studies a specific control program such as a federal or state regulation. a new piece of equipment or an improved industrial process to reduce air pollution. Within a CBA, it is relatively simple to determine the cost of a control program or equipment. Stern (1968) says that "most of the governmental cost for air pollution control, research, and prevention are rather well defined." Estimates of economic effects are based on data for pollution abatement investments and expenditures after subtracting control costs that would have been incurred regardless of regulations or air pollution control programs (NCAQ 1981). However. in order to determine the economic losses due to air pollution or the economic benefits due to control programs, researchers differ in the way they assign economic values to the affected people, animals, vegetation, and materials

(Stern 1968. Ahmad 1981, NCAQ 1981). These economic values vary within a country and from country to country depending on the abundance of natural resources, market prices and the purpose of the study. Halvorsen and Ruby (1981) state that the benefits and control of an air-pollution-control program may take different forms, occur at different times, involve different degrees of uncertainty, and affect different individuals.

Stern (1968) examined some of the problems involved in translating a qualitative observation of damage into a quantitative estimate of cost and gave general guidelines to approach this problem. He said that if the mechanism of damage is used as a starting point, the most pertinent variables, such as pollutants, moisture, temperature and sunlight, should be considered first. Second, these variables have to be evaluated and the relative contribution of a particular pollutant or combination of pollutants has to be determined. Third, a survey should be required to determine the extent of damage. He pointed out that "the cost of damage might be represented either by a shortened useful life or by protective measures such as over design, protective coating, substitution of materials, or reduced market value." Finally, he suggested that these damages need to be translated into dollar values, and a proper basis for extrapolation must be developed before the various components can be summed up on a larger scale. Even though Stern's guidelines can be applied and related to many studies to determine benefits and economic losses, there are still many limitations; human health, aesthetic and recreational values make it complex to determine the economic benefits of a program or the economic losses due to air pollution (Strauss 1984, Ahmad 1981. Halvorsen and Ruby 1981, NCAQ 1981).

The National Commission on Air Quality (NCAQ 1981) found many problems associated with the methodology of estimating benefits of the U.S. Clean Air Act's programs. These problems were listed as follows: "calculating health benefits, which entails applying and analyzing data on ambient pollution levels; correlating human health and air pollutants; and calculating the cost of morbidity and mortality." The NCAQ concluded:

- Both costs and benefits of the Act's programs have been significant.
- Quantification of all costs and benefits of any air pollution control program are virtually impossible.
- Necessary data to make reasonably accurate cost and benefit comparisons are not likely to be available in the foreseeable future because a number of relevant variables cannot be easily measured (NCAQ, 1981).

The NCAQ (1981) observed that benefits estimates are best reported as approximations and ranges, instead of absolute numbers, because of the uncertainty associated with data and the conversion of effects to monetary values. For example, the NCAQ found that in the U.S., the range of economic benefits for air pollution control was from $5 billion to $51 billion. Benefits include improvements to human health, reduced soiling and cleaning costs for households, reduced damage to vegetation and crops, and reduced damage to non-aesthetic materials.

**2.1.4.1 Health Costs and Benefits**

Ahmad (1981) reviewed an extensive document submitted by the United States to the UNEP to establish the conceptual foundations for estimating national damages from air pollution. He found that the damages to human health caused by air pollution were considered to be the most undervalued categories of air pollution damages. The effects were increased prevalence and incidence of disease (morbidity) and mortality. The common indicators of morbidity were absenteeism, hospital admission and length of stay, visits to physicians, expenditures in certain drugs, automobile accidents and reduced productivity. Ahmad stated that "although quantitative relationships between the specific disease and air pollution levels had been explored in a number of studies, only a few yielded quantitative information suitable for estimation of damage."

The NCAQ (1981) stated that "health benefits alone comprised the majority of total benefits estimated from air pollution control." This statement was based on the analysis of several studies (Crocker, Shultze, Shaul, and Kneese 1979, Freeman 1979). In the United States, Crocker et al. (1979) reported annual national benefits to be $16 billion for a 60% reduction in air pollutants in urban areas with a total population of 150 million; an individual life was assigned a value of $1 million. A different study that considered worker productivity, namely, the effects of reduced absenteeism and illness, reported yearly national health benefits of $43 billion (Croker et al., 1979). Based on Freeman's study (1979), the NCAQ reported that health benefits varied from $3 billion to $40 billion annually for a 20% reduction of air pollution levels between 1970 and 1978, when socioeconomic and lifestyle factors, such as diet and smoking were considered. For studies taking into account factors such as medical costs, loss of earnings due to illness, cost of temporary household help required during illness, and other less significant costs, the range of annual health benefits is between $3 billion and $43 billion (NCAQ 1981). In 1989, the Office of Technology Assessment estimated that the value of the health benefits to be obtained by meeting federal ozone standards could range between $1.3 billion and 9.5 billion annually (GAO 1993).

**2.1.4.2 Vegetation Costs and Benefits**

Amhad (1981) observed that studies on the effects on crops and ornamental plants had yielded inconsistent results, and exhibited wide variations among the various strains and conditions of growth. He said that determination of effects had been based largely on measure of extent of leaf injury and many indices had been developed to relate this measure to yield loss. Nevertheless, he found that substantial losses of fruit, grain and timber had been observed even in the absence of significant leaf injury, so the latter could not be used reliably as an indiscriminate measure for yield loss. On the other hand, Stern (1968) believes that cost from vegetation damage in areas where agricultural crops and ornamental flowers are grown could be determined relatively easily. However, he thinks that damage to vegetation where a crop of no direct economic value is involved, such as city parks and home flower gardens, is difficult to appraise.

In the United States, the NCAQ (1981) undertook a study to obtain estimates of damage to crops. This study found the approximate value of damage reduction of 19 food and fiber commercial crops from meeting air quality standards in 1978 to be $1.78 billion; the total market value of these crops was $54 billion. It was reported that ozone caused

98% of the damage to crops. The states significantly affected by pollution crop damage were Ohio, Indiana, Illinois, Michigan, and Wisconsin. This region reported approximately 41% ($731 million) of all crop damage. The Pacific region (California, Oregon, Washington, Alaska, and Hawaii) was the next most affected with $384 million in pollution damages, about 22% of all crop damages. The rest of the states were less affected by pollution damage. The US Environmental Protection Agency estimated the loss of vegetation and livestock production at $325 million and $175 million respectively (Strauss 1984).

#### 2.1.4.3 Material Costs and Benefits

Amhad (1981) reported that the aesthetic damages from air pollution were considered extremely difficult to quantify and that the economic impact was usually measured in terms of willingness to pay for abatement estimated through opinion surveys or surveys of property values. However, estimation of the damage to non-aesthetic materials was less problematical (Amhad 1981). The NCAQ (1981) found that in the United States, the value of damages avoided by meeting air quality standards for selected metals, fabric, building materials, rubber and plastics was $ 3.95 billion.

## 2.2 Mexico City and Its Air

### 2.2.1 Demographic and Topographical Conditions in MCMA

Mexico City has approximately 19.37 million inhabitants (more than one-fifth of Mexico's total population), 2.2% annual population growth rate, and population densities ranging from almost 7,000 persons per square kilometer in the center to 500 persons per square kilometer in the outskirts. Mexico City and its Metropolitan Area (MCMA) has approximately 30,000 industries of all type and sizes and about 3.5 million vehicles--buses. minibuses, taxis, trucks, vans, and private cars-- circulating every day.

MCMA sits in a basin at a mean altitude of 2,240 meters. The Mexican basin is surrounded by mountains, two of which rise to more than 5,000 meters. Two valley channels located in the north funnel air to the center and to the southwest of the city. The UNEP-WHO (1994) reported that because of Mexico City's topography and light winds, "ventilation is poor, and surface as well as upper air temperature inversions occur frequently." During the winter, inversions take place up to 25 days per month. The continued enlargement of the urban area and consumption of electricity have significantly modified the Mexican valley's microclimate. Hot spots reach up to 12°C above the temperature in suburban and rural areas due to the heat island effect. All these climatological and topographical conditions trap air pollutants close to the city. Moreover, given its topography, climate, and relatively high oxides of nitrogen emissions, Mexico City has ideal conditions for the generation of $O_3$ (UNEP-WHO 1994).

### 2.2.2 Air Conditions in MCMA

Mexico City started monitoring air pollution in the 1950's. The monitoring of air pollution became more systematic in the 1960's. With the support of international organizations such as the Pan American Health Organization and the United Nations, Mexico increased the number and quality of monitoring stations by the 1970's. However, the only air pollutants which could be monitored were suspended particle matter (SPM), and sulfur dioxide ($SO_2$). In 1985, with technical assistance from the U.S. Environmental Protection Agency (EPA), an automatic monitoring network was developed. This network, called the Red

Automatica. measures $SO_2$, carbon monoxide (CO), ozone ($O_3$), oxides of nitrogen (NOx), and non-methane hydrocarbons (NMHC) (UNEP-WHO 1994).

To assess the problems of urban air pollution in the world's largest cities, the United Nations and the World Health Organization carried out a study (UNEP/WHO 1994). Their study found the concentration of several air pollutants in the metropolitan area of Mexico City. The pollutants by sources and their amounts produced per year are shown in Table 2.3. Table 2.4 shows the percentage of pollutants emitted by sector. In these tables it is noted that the main source of most air pollutants is the transportation sector. The results obtained for each air pollutant in the UNEP/WHO's study are described below.

**Sulfur Dioxide ($SO_2$).** From 1986 to 1991, five sites from the monitoring network measured $SO_2$ levels from 50 to 160 $\mu g/m^3$. Theses measures are well above the guidelines levels values set by the WHO, 40 to 60 $\mu g/m^3$ in one year. Mean levels of $SO_2$ range in the central area from 80 to 200 $\mu g/m^3$, and daily maxima are between 200 and 550 $\mu g/m^3$ well above the WHO permissible levels per day, 100 to 150 $\mu g/m^3$.

**Suspended Particle Matter (SPM).** From 1976 to 1991, a concentration rate between 100 and 500 $\mu g/m^3$ was reported. It was also noted that the national air quality standards and the WHO guidelines for SPM were frequently exceeded. The WHO permissible limits for SPM per year range from 40 to 60 $\mu g/m^3$.

**Carbon Monoxide (CO).** National air quality standards and WHO guidelines, 30 $mg/m^3$ in one hour, were also exceeded at several monitor sites. Data related to commuters exposure to CO show one-hour concentrations of up to 67 milligrams per cubic meter of

Table 2.3 Emission Inventory for Mexico City and its Metropolitan Area, 1990. (Gobierno de la Republica, Programa Integral Contra la Contaminacion Atmosferica, Mexico D.F., 1990).

| Sector | Sulfur dioxide | Suspended particulate matter | Carbon monoxide | Oxides of nitrogen | Non-methane hydrocarbon |
|---|---|---|---|---|---|
| | (thousand tons per year) | | | | |
| **Energy** | | | | | |
| PEMEX[a] | 14.7 | 1.1 | 52.6 | 3.2 | 31.7 |
| Power Plants[b] | 58.2 | 3.5 | 0.5 | 6.6 | 0.1 |
| **Industry** | | | | | |
| Industry | 65.7 | 10.2 | 15.8 | 28.8 | 39.9 |
| Services | 22.0 | 2.4 | 0.4 | 3.9 | 0.1 |
| **Transport** | | | | | |
| Private cars | 3.5 | 4.4 | 1,328.1 | 41.9 | 141.0 |
| Taxis | 0.8 | 1.0 | 301.1 | 9.5 | 31.9 |
| Combis and minibuses | 0.8 | 1.0 | 404.4 | 10.0 | 42.7 |
| Urban buses | 5.2 | 0.2 | 6.2 | 8.0 | 2.4 |
| Suburban buses | 13.0 | 0.6 | 12.6 | 18.2 | 5.3 |
| Gasoline trucks | 0.9 | 1.1 | 779.5 | 16.9 | 67.8 |
| Diesel trucks | 20.0 | 0.9 | 16.5 | 26.1 | 7.6 |
| Other | 0.2 | 0.1 | 5.0 | 2.7 | 1.6 |
| **Environmental degradation** | | | | | |
| Erosion | 0.0 | 419.4 | 0.0 | 0.0 | 0.0 |
| Forest fires, etc. | 0.1 | 4.2 | 27.3 | 0.9 | 199.7 |
| TOTAL | **205.7** | **450.6** | **2,950.6** | **177.3** | **572.1** |

[a] Closed in 1991

[b] Switched to Natural gas in 1991

Table 2.4 Percentage of Pollution by Sectors in MCMA. (UNEP/WHO 1994).

| | CO % | $NO_x$ % | NMHC % | $SO_2$ % | SPM % |
|---|---|---|---|---|---|
| Transport | 96.7 | 75.2 | 52.4 | 21.6 | 2.2 |
| Energy | 1.8 | 5.5 | 5.5 | 35.4 | 1.0 |
| Industry | 0.55 | 18.4 | 7 | 42.6 | 2.8 |
| Nature | 0.9 | 0.5 | 35 | 0.04 | 94 |
| **Total** (%) | **100** | **100** | **100** | **100** | **100** |

air ($mg/m^3$). CO levels peak on weekdays between 7:00 and 9:00 a.m., when low temperatures, atmospheric stability (inversions), and heavy vehicular traffic occur simultaneously. There is another peak in the evening, but it is lower than the one in the morning. Mexico City has low oxygen content in its atmosphere because of its altitude. This situation causes CO emissions to increase because of incomplete fuel combustion.

**Nitrogen Dioxide ($NO_2$).** Mean $NO_2$ levels range from 113 to 207 $\mu g/m^3$, while hourly levels range from 301 to 714 $\mu g/m^3$. The latter are frequently above the WHO guideline of 400 $\mu g/m^3$ and the national air quality standard of 395 $\mu g/m^3$.

**Ozone ($O_3$).** Ozone levels in the city are extremely high. From 1986 to 1990, the annual mean of $O_3$ fluctuated around 200 $\mu g/m^3$, with lows around 100 $\mu g/m^3$ and highs between 300 and 400 $\mu g/m^3$. Hourly $O_3$ levels often reach 600 $\mu g/m^3$, and extreme values have been measured at up to 900 $\mu g/m^3$- four times the WHO guidelines. In 1988, certain areas of Mexico City exceeded the national air quality standards on 70% of the days of the year.

**Lead.** The UNEP/WHO (1994) pointed that there were few routine data on lead in ambient air; they said that "Most information comes from special investigations into lead's effects on the mental development of infants and children." The available information on airborne lead in Mexico City shows that lead levels frequently meet the national quarterly evaluation standard of 1.5 $\mu g/m^3$; however, these levels are somewhat above the WHO guidelines, 1 $\mu g/m^3$. It was noticed that gasoline-powered motor vehicles were the major source of ambient lead in Mexico City.

### 2.2.3 Measures Taken to Reduce Air Pollution in MCMA

In November 1989, as part of the Plan de Contingencia Ambiental (Emergency Environmental Plan), a program called "Hoy no Circula" or "A Day Without a Car" was created. This program takes cars out of circulation one day per week according to license plate number. Because of this program 450,000 vehicles are out of circulation every day. Initially, the program was intended to be in effect only for four months per year (during the winter season), but given the year long pollution problem, the Mexican government made it a permanent program in March 1990 (USDOC 1994). As a result of this program, people started to buy more cars so that they can use a vehicle every day; consequently, the intended objective of this program was not satisfactorily accomplished. During 1991, sales of vehicles reached the highest number in history, selling 642,981 units, an increase of 16.8 percent from 1990 (USDOC 1994). In addition, the BNA (1993) reported that an economist at the World Bank's Country Economics Department found that the additional cars that people had bought as a result of the "Day Without a Car" program were often already several years old. Since old cars are more likely to emit a greater amount of pollution than newer cars, the results were not as favorable as expected.

Another mandatory program, introduced in 1990, is the "Programa de Verificacion Vehicular" (Auto Emission Testing Program). This program required that every conventional vehicle circulating in MCMA and trucks running on the federal highways be inspected biannually (USDOC 1994). After lead-free gasoline was introduced in 1990, automobile manufacturers were also forced to include auto emission control devices (catalytic convertors) in every 1991 or newer model car (USDOC 1994). Event though this measure has reduced levels of pollution somewhat, the results have not been as efficient as expected. Lead-free gasoline was introduced to the market, but its use was not enforced for all vehicles. Baker and van Aardenne (1993) reported that most catalytic convertors are no longer functioning, due to the common use of poorly refined leaded gasoline. They observed that while in the U.S. most cars have high-efficiency fuel injectors, in MCMA most vehicles still come with carburetors. USDOC (1994) reported that at the end of 1993, 90% of the vehicles (approximately 2.5 million vehicles) that circulated in MCMA did not have catalytic convertors. The USDOC also pointed out that it will be difficult to install catalytic convertors without creating other mechanical problems since the age of the average Mexican vehicle is estimated to be between 10 and 15 years old.

Moreover, car maintenance practices are not carried out as frequently in Mexico as they are in the U.S. In a study made by the U.S. Environmental Protection Agency (EPA) and the Mexican Secretariat of Ecology and Urban Development (SEDUE) in 1990, it was found that combustion emissions of average vehicles in a urban city of Mexico were equivalent to early or mid-1970s levels of U.S. cars (Baker et al. 1993). Based on this finding, it can be stated that by introducing EV's in MCMA under a program similar to the ZEV from California, reductions in annual emissions will be greater than the reductions that will be achieved in Los Angeles using the same program.

### 2.2.4 Economic, Health and Social Issues Associated with Air Pollution in MCMA

In the last few years, environmental degradation has become a major concern of Mexicans and their government. Mexico spent close to 1% of its gross national product (GNP) on clean up programs in 1993. This compares with only 0.10-0.14% seven years ago

(Parkinson 1993). Mexico public investment in environmental affairs increased from \$95 million in 1988 to \$2.5 billion in 1993 (USDOC 1995). The relatively new emphasis of the Mexican government on controlling air pollution means increased public and private sector spending forced by creating more regulations and enforcement. In October 1990, the Comprehensive Program Against Atmospheric Pollution was implemented with the cooperation and commitment of all sectors of society. "Overall, the program has an investment budget of \$4.7 billion for 1991-1995, of which... \$1.7 billion was spent from 1991 to the end of 1993" (USDOC 1995).

Since auto emissions contribute approximately 75% of the total pollution in Mexico City, auto emission control has become one of the highest priorities for the Mexican Air Pollution Control Authorities D.D.F. (Federal District Department) and SEDESOL (Secretariat for Social Development). The USDOC (1995) reported that the total market for auto-emission control equipment increased from \$12.8 million in 1990 to \$36.5 million in 1992. This market is expected to continue growing at an annual average rate of 20% in the coming years. Parkinson (1993) said that Petroleos Mexicanos (PEMEX), the government oil-company, "is investing \$1.1 billion in an 'ecological package,' designed to reduce pollution by increasing the production of unleaded gasoline and low-sulfur diesel fuel, and by cleaning up its refinery operations."

Although Mexicans are making an effort to reduce air pollution in MCMA and have significantly invested in air pollution control programs, the high levels of pollution keep threatening the well being of the residents of MCMA. The environmental situation of MCMA has made national and international firms look for better places to relocate or start their businesses. Statland (1991) states that "it's not easy to convince foreigners to make their home in a city with dangerous levels of lead, ozone and other air pollutants.... [For this reason] companies and institutions are developing new plans to compensate employees for the 'quality of life' drawbacks of the world's largest city." Currently, the American Embassy offers a 10% salary differential based upon environmental considerations. Southwestern Bell's health package includes voluntary testing for lead levels in the blood; this testing is offered by many other companies, especially for children who are more susceptible to lead in their blood. Several companies are providing their employees with air filters; if employees prefer a different filter, some companies give employees a certain allowance which they can use toward its purchase. Other companies offer extra income for weekends away from Mexico City. The Japanese Embassy offers its employees four-day paid vacations to Acapulco every four months because of air pollution and altitude. The New Zealand Embassy personnel get an escape weekend per month to get the pollution out of their system. Many companies provide annual medical check-ups. In contrast, "most companies... do not provide the same benefits to Mexican employees, although researchers indicate that the human body does not develop immunity to the harmful effects of atmospheric pollution..." (Statland 1991).

The head of the International Relocation Service in Mexico City completed a survey concerning the effects of pollution on newly arrived families in March 1991 (Statland 1991). It was found that the effects on these new residents were irritated eyes, sinus problems, headaches, a chronic cough, short-term memory loss, high lead count, lethargy, lower resistance to illness, breathing difficulties and respiratory ailments.

## 2.3 Electric Vehicle Background

EV's were relatively common for many types of transportation from the late 1880's to about 1918. However because of internal-combustion-vehicle innovations, EV's lost most of their marketplace by 1935. From the beginning of the 1920's to the early 1990's, there was no significant investment in R&D for EV's; hence, few advances were made. After California approved its Zero Emission Vehicle (ZEV) mandate in 1990, major investments in R&D for EV's have been made and significant improvements in EV technology have resulted. In this section, technological characteristics, performances, prices and drawbacks of current EV's are discussed.

### 2.3.1 Technology and Performance of EV's

The electric vehicle is a system that is formed by four main components, namely, the vehicle body, electric propulsion, an energy storage battery, and energy management. Because of the nature of these components, the technologies involved in the EV system are diverse; related areas include electrical and electronic engineering, mechanical and automobile engineering, and chemical engineering. However, system integration and optimization have enabled perfect matching among subsystems even though many components used in EV's work in mobile and severe temperature conditions (Chan 1993).

The overall goal of EV development is to manufacture commercially viable EV's over the long term. This means EV's must provide performance, personal comfort, and safe, trouble-free operations similar to or better than ICV's at a competitive price. Table 2.5 shows the characteristics of EV's. Besides the environmental advantages that EV's offer by not emitting pollutants when driven, there are other factors that favor these vehicles; EV's are quieter, more reliable and require less maintenance than the ICV's. Riezenman (1992) says that "there is no comparison between the simplicity of an electric motor controlled by solid state electronics and the complexity of an internal combustion engine, with its multiplicity of fuel injectors, [carburetors], compressors, pumps, and valves (which get more numerous and complex with every effort to make the engine less polluting)." In addition, EV's do not have a water cooling system to maintain; filters, belts or hoses to replace; or oil to change or to thicken in cold weather.

EV's are also more energy efficient than conventional vehicles. The conversion of chemical energy into mechanical energy is simply less efficient than the conversion of electricity to mechanical energy. Electric motors are about 90% efficient, compared to less than 25% for ICV's. Furthermore, Sperling (1995a) reported that EV's "can capture as much as half the energy lost during braking (regenerative braking); they do not need a transmission, which reduces energy used by another 6 percent or so; and they do not consume energy during idling and coasting, saving still another 10 percent."

### 2.3.2 EV's Drawbacks

All of the EV's characteristics mentioned so far are favorable and make EV's attractive. However, there are two main practical reasons why EV's are at a disadvantage when compared to their ICV's counterparts. First, EV's cannot go nearly as far on a single charge as comparable ICV's can go on a tank of fuel. For instance, the range of current EV's using lead/acid batteries is only from 80 to 140 km (50 to 87 mi) per charge with a top speed of 113 and 104 km/h (70 and 65 mi/h) respectively. Riezenman (1992) explained this disadvantage by comparing the energy density of hydrocarbon fuels with available

Table 2.5 Characteristics of EV's. (Riezenman 1992, pg. 95).

| Vehicle | Developer | Type | Status | Battery | Range Km | Top speed Km/hr | Comments |
|---|---|---|---|---|---|---|---|
| BMW E1/E2 | BMW AG (Germany),Unique Mobility (U S ) | 4-passenger car | Concept, no production plans announced | Sodium/Sulfur | 240 | 120 (E1) | E1 uses a 32-KW permanent magnetic dc-motor |
| Ecostar | Ford Motor Co (U S ) | Minivan based on Ford's European Escort | 80-100 will be produced in 1993 and leased for 30 months | Sodium/Sulfur | 160 | 120 (governed) | Use a 3Ø, 56KW ac-ind motor integrated into front transaxle |
| Fiat Panda Electra | Fiat SpA (Italy) | Passenger car | production run of 500 planned | Lead/Acid<br>Nickel/Cadmium | 80<br>104 (City driving) | 113 | Uses a 9 2-KW ac series dc-motor |
| GM Impact | GM, Aero- Vironment Inc (U S ) | 2-seater subcompact sports car | commercial, production in mid-1990s | Lead/acid | 190 (at 90 Km/hr) | 120 (governed) | Uses two 43-KW ac induction motor |
| G-Van | EPRI, GM Corp (U S ), Conceptor Industries Inc (Canada) | Passenger/cargo van based on GM ventura glider | about 100 in commercial fleets-mostly utilities | Lead/Acid | 96 (City driving) | 83 | Uses a 43-KW dc-motor |
| LA 301 | LADWP, SCE, Clean Air Transport (U S ) | 2-passenger, series hybrid car | Commercial production projected for 1993 | Lead/Acid<br>Sodium/Sulfur | 96<br>154 | 97 | Hybrid version with sodium/sulfur battery and auxiliary ICE has range of 240 Km |
| Mercedes Benz 190EV | Mercedes Benz AG (Germany) | 5-passenger, 4-door car | Research car | Sodium/Nickel Chlonde | 150 | 120 | Uses two external-rotor dc-motor |
| Nissan FEV | Nissan Motor Co (Japan) | passenger car | Concept, no production plans announced | Nickel/Cadmium | 160 at 72 Km/Hr | 120 | Can accept a 40% charge in 6 min , has solar cells in roof to augment battery |
| Renault Zoom | Renault (France), Matra SA (France) | 2-Passenger car | Concept, production version under development | Nickel/Cadmium | 150 | 120 | Wheelbase shortens from 1845 to 1245 mm for parking |
| Tepco Iza | Tokio Electric Power Co (Japan) | 4-passenger car | Concept car, only one built | Nickel/Cadmium | 550 at 40Km/Hr | 176 | Has 25-Kw brushless dc motor inside each wheel |
| TEVan | EPRI, Chrysler Corp ,SCE (U S ) | Passenger/cargo minivan based on Chrysler minivan glider | About 50 will be produced in 1993 | Nickel/Iron | 180 | 105 | Uses a 46-KW dc motor |
| VolksWagen CityStroner | VolksWagen AG (Germany) | Passenger car | 70 vehicles using lead/acid battery built and sold | Lead/Acid<br>Sodium/Sulfur | 140<br>120 | 104 | Based on jetta production vehicle |

electrochemical batteries. He said that a typical lead/acid battery has a specific energy of only 30-35 Wh/kg, and even other more efficient batteries such as sodium/sulfur check in at about 80-85 Wh/kg, while gasoline packs about 12,000 Wh/kg without considering the weight of the gas tank.

The second reason EV's are at a disadvantage when compared to ICV's is that it takes much longer to recharge an EV's battery than it does to fill a gas tank. Riezenman (1992) said that for varied reasons, all the batteries used in EV's are slow to recharge. He explained that with some types of batteries, charging is accompanied by the evolution of gas, and must proceed slowly enough for the gas to recombine as fast as it is generated With others the main obstacle is overheating which limits the capacity of the recharger. In order to achieve 40 to 45% recharging in some advanced batteries it takes at least 15 minutes (quick charging).

Another disadvantage is the starting market price of EV's. Initial EV's market prices are expected to be higher than ICV's prices. The price differences range between $5,000 to $10, 000 for vehicles with similar characteristics such as passengers capacity, top speed, air conditioning, etc. (Sperling 1994, Terpstra 1993). Table 2.6 gives an idea of how EV's prices differ from a comparable gasoline vehicle price. The cost of EV's and their performance significantly depend on the type of battery. For this reason, research to improve current battery technologies and develop new electrochemical power sources is currently being supported by the automobile industry and the U.S. government.

### 2.3.3 Battery Characteristic

The battery is the main technological disadvantage of EV's. It is believed that the future acceptance of EV's will basically be determined by the technical progress of electric drive systems for which the development of the batteries represent a key issue (Kruger and Gereth 1994). Hampton (1993) said that "preparing a vehicle for an electric propulsion system is not difficult. But coming up with a powerful enough battery system is another matter." So far, lead-acid has been the only commercially available and mature battery technology suitable for EV's (Chan 1993, Terpstra 1993, and Riezenman 1992).

In 1993, Chan reported the following: lead-acid batteries would last for about 48 thousand km (30 thousand miles) with deep discharging cycles, the life cycle of these batteries was about 750 cycles, and their energy density and peak power density at 50% depth-of-discharge were 33 Wh/kg and 93 W/kg. Terpstra (1993) found that lead-acid batteries must be replaced every 20,000 to 30,000 miles. He said that in a small car, this can cost from \$500 to \$1,500, depending on the type and quantity of batteries. Terpstra said that the cost of battery replacement was not significantly different from the maintenance costs of ICV's when considering oil and filter changes, tune-ups, replacement of spark plugs, etc. for the same number of miles traveled. However, he recognized that new battery technology is needed to improve EV's performance.

Table 2.6 Price of Subcompact Electric Vehicles Versus a Gasoline-Power Car. (Sperling 1995, pg. 57)

| | | Near Term | | Medium Term | | Long Term | |
|---|---|---|---|---|---|---|---|
| | Gasoline | Low | High | Low | High | Low | High |
| Battery | -- | Lead Acid | | Nickel-metal hydride | | Lithium Sulfide | |
| Range (miles) | 300 | 100 | 100 | 75 | 125 | 100 | 200 |
| Purchase cost with battery $ | 12,944 | 17,761 | 21,775 | 15,769 | 21,124 | 15,685 | 18,916 |
| cent/mile | 26.7 | 29.9 | 36.8 | 25.8 | 33.0 | 27.8 | 29.9 |

In 1991, Chrysler, Ford and General Motors formed the United States Advanced Battery Consortium (USABC) in order to assist with the development of better battery technologies to increase energy and power capability, extend the life, and reduce the cost of batteries (Sperling 1994 and Hampton 1993). In October 1991, recognizing that the U.S. automobile industry is a key factor for the health of the nation's economy, and the importance of electric vehicles for the automobile industry, the U.S. Department of Energy, Washington, D.C., joined forces with the USABC. The Electric Power Research Institute (EPRI), Palo Alto, California, also joined the USABC in 1991. Sperling (1994) stated that the USABC's budget called for $230 million to be spent by 1995 and $100 million to be spent per year into the early years of the next century.

Riezenman (1992) reported that what the USABC has done is to survey the scores of electrochemical technologies that could be used to build EV batteries and categorize them as mature (near-term), developmental (mid-term), or experimental (long-term). The USABC examined the mid-term and long-term technologies to pick the most promising, and then began awarding contracts to research organizations to develop the selected technologies. The "USABC's definition of mid-term technology is one 'which will result in mass production of... EV batteries potentially in this decade.' A long-term technology is one 'with performance competitive with today's internal combustion engines and capable of commercial production early in the next decade.'" (Riezenman 1992). Tables 2.7 and 2.8 describe the criteria of the USABC and the performance projections of batteries for EV's.

The development of battery technologies continues, with research being done to improve nickel-zinc, nickel-iron, lithium, aluminum-air, and zinc-air batteries (Terpstra 1993). The technologies most often classified within the mid-term category are nickel/iron, sodium/sulfur, zinc/bromine, nickel/metalhydride, and lithium/iron monosulfied. For the long-term category, it is lithium in one form or another: lithium-aluminum/iron disulfide, lithium/iron disulfide, lithium-aluminum/polymer, or lithium/polymer (Riezenman 1992). Characteristics like safety, cost-effectiveness, availability, recyclability, material toxicity, ability for sealed operation, energy density, cycle life, and specific power all impact the final selection of one system over the other (Kruger and Gereth 1994, Chan 1993, Riezenman 1992). Although many of these technologies are being developed and tested, it is thought that lead-acid batteries will still dominate in the near future.

Kruger and Gereth (1994) compared three technologies which eventually may be used in commercial EV's. The accumulators analyzed were lead-acid, nickel metal-hydride, and lithium-ion batteries which are classified as near-term, mid-term, and long-term technologies respectively. They reported that in addition to energy density, the three battery systems differed with respect to performance properties such as rate capability and fast rechargability, as well as price and availability.

**Specific Power.** With continuous discharge capabilities of up to 300 W/kg, the nickel metal-hydride is superior to the other two systems.

**Quick Charge.** For lead-acid batteries, a charging time of eight hours is typical. Generally, lithium-ion batteries can be recharged in two to four hours. The alkaline nickel

Table 2.7 Criteria of U.S. Advance Battery Consortium.
(Chan 1993, pg. 1210)

| **Criteria** | **Mid-Term** | **Long-term** |
|---|---|---|
| Primary criteria | | |
| Power density, W/L | 250 | 600 |
| Specific power, W/Kg (80% DOD/30s)[a] | 150 (200 desired) | 400 |
| Energy density Wh/L (C/3 discharge rate)[b] | 135 | 300 |
| Specific energy, Wh/Kg (C/3 discharge rate) | 80 (100 desired) | 200 |
| Cycle life, cycles | 600 (5 years) | 1000 (10 years) |
| Ultimate price, US$/kWh | <150 | <100 |
| Operating environment, °C | -30 to 65 | -40 to 85 |
| Recharge time, h | <6 | 3 to 6 |
| Continuous discharge, % of rated energy capacity no failure | 75 | 75 |
| **Secondary Criteria** | | |
| Efficiency, % (C/3 discharge, 6-h charge) | 75 | 80 |
| Self-discharge | <15% in 48 h | <15% per month |
| Maintenance | zero | zero |

[a] C/x Discharge Rate: The current that will completely discharge a fully charge battery in 'x' hours. For example, a battery with a capacity of 100 ampere-hour has a C/4 rate of 25 A.

[b] Depth of Discharge (DOD): The percentage of full ampere-hour capacity that has been withdrawn from a battery.

Table 2.8 Performance Projections of Batteries for EV's in Year 1992 and 2000.
(Chan 1993, pg. 1211)

| | | | Pb-Acid | Ni-Fe | Ni-Cd | Ni-MH | Zn-Br | Na-S | Li-FeS | Li-$FeS_2$ |
|---|---|---|---|---|---|---|---|---|---|---|
| Cycle life(Cycle) | | 1992 | 50-1500 | 300-1000 | 2000 | 500+ | 200-2000 | 800+ | 1000 | 1000 |
| | | 2000 | 200-2000 | 1200 | 3000 | 1000 | 1000 | 1200 | | |
| Calendar life (year) | | 1992 | 20 | 6 | 20 | 5 | 1 | 1 | 1 | 1 |
| | | 2000 | 20 | 10 | 25 | 10 | | 10 | 6~10 | 6~10 |
| Energy density (at C/5 rate) | Gravimetric (Wh/Kg) | 1992 | 30* | 53* | 40* | 60* | 70 | 80-100** | 100* | 115* |
| | | 2000 | 50* | 60* | 55* | 65* | 80* | 175** | 100* | 175* |
| | Volumetric (Wh/L) | 1992 | 85 | 120 | 70 | 120 | 56 | 110-130 | 110 | 245 |
| | | 2000 | 100 | 130 | 75 | 120 | 100 | 265 | 150 | 400 |
| Power density (W/Kg) | | 1992 | 250 | 100 | 260 | 100 | 70 | 250 | 107 | 600 |
| | | 2000 | 400 | 110 | 300 | 150 | 100 | 400 | 110 | 600 |
| Cost (USS per kWh) in 1992 USS | | 1992 | 200 | 500 | 2000 | 3500 | 110 | 2000* | | |
| | | 2000 | 150 | 200 | 1500 | 2500 | | 150 | | |

* Cell basis.

** Battery basis

metal-hydride systems can be recharged in one hour. Charging of nickel metal-hydride batteries to 75% state of charge may be possible within 10 minutes.

**Cost.** In large scale production, the price of lead-acid batteries is estimated to be \$150 per kWh. The price of a nickel metal-hydride will be in the range of \$600 to \$800 per kWh. The lithium-ion system aims at prices of less than \$500 per kWh as mid-term goal.

**Availability.** In terms of hardware and production development, the lead-acid battery is the most mature technology. The nickel metal-hydride technology is in an advanced research state. Existing nickel cadmium facilities can be used to produce nickel metal hydride batteries on a large scale. Large lithium-ion cells and batteries are still in the early stages of development. Mass production of lithium based batteries is not expected before the end of the century.

Since there will be different types of electric vehicles to satisfy a variety of customers' needs and preferences, a single battery system will not serve all markets. Consequently, depending on the predominant characteristics of a specific region such as topography, infrastructure, climate, traffic patterns, etc., a particular battery has to be selected. May and Courty (1994) presented four stages for battery selection: 1) analysis of the vehicle application requirements, 2) analysis of the function of the battery within the vehicle, 3) analysis of the infrastructure constraints, and 4) analysis of the information required by the user for effective operation.

The consideration of all these parameters will define the battery technology. Operational constraints of cost range, availability, servicing and ease of use will also determine the choice among available batteries.

## 2.4 Environmental and Economic Studies of EV's

When analyzing the environmental impact of electric vehicles on a urban area, the major factor which needs to be considered is the increase of electric power demand due to the new EV's on the road. Finding out how much air pollution will be generated in order to satisfy the new demand of electricity is the main concern of most EV's environmental studies. For economic analysis, besides the EV's direct and operational costs, a major cost is the infrastructure that EV's require within a city such as special parking places, electric outlets, transformers and recharge centers. The following sections discuss current studies carried out to determine the environmental and economic impact of EV's.

### 2.4.1 Environmental Effects of EV's

EV's are called zero emission vehicles since they do not emit pollutants from their tail pipe; however, the electricity they consume is generated by different types of power plants which are significant sources of air pollution in many urban areas. Many of these plants use oil, hard coal, brown coal and natural gas as primary sources of energy. According to Wenger and Chang (1994) other possible sources of air pollution associated with EV's include vehicle manufacturing, and battery recycling.

Wenger and Chang stated that "manufacturing emissions are difficult to quantify, but will presumably be similar to those from the manufacture of conventional vehicles." Also, they reported that the California Air Resource Board (ARB) completed a preliminary study of battery recycling emissions from lead-acid batteries, and found that lead-acid battery recycling emissions associated with EV's use are expected to be minimal. In addition, the ARB is funding a project to examine battery recycling emissions from a number of different battery technologies, including nickel- and lithium-based (Wenger and Chang 1994).

Many studies (Hayashi et al. 1994, Morrow and Dekoster 1994, Prakash et al. 1994, Sporckmann 1994, Wenger and Chang 1994) have found that the primary source of emission associated with EV's is from power plants generating electricity for EV charging. It was pointed out that power plant emissions associated with EV's will vary depending on the types of fuels used to generate electricity, and the level of emission control at the power plant. For instance, a comparison of primary energy consumption between natural gas and coal gives a poor result for coal in almost all cases (Sporckmann 1994).

Most of the studies differ when considering or choosing the type of power plant and its primary energy. For instance, Wenger and Chang (1994) reported that the ARB's analysis did not consider a single source of electric generation; instead they considered the average power mix used in the South Cost Air Basin (SCAB) of California. Sporckmann (1994) also used a power mix to study the emission of electric vehicles but he considered the power mix from 14 European countries, which resulted in a different configuration of the types of power plants and primary energy sources from the configuration used by ARB in California. Morrow and Dekoster (1994) looked at three types of primary energy sources (coal, gas and oil). Another study carried out by Hayashi et al. (1994) considered only oil as the primary energy source.

Prakash et al. (1994) examined various types of power stations located in Ontario. The amount of energy generated by specific types of power plants from Ontario differs from the amounts or percentages used in other studies. For example, in Prakash's study 1%

of electricity was generated with oil, 1.3% with natural gas, 24.1% with coal, 27.3% with hydro-power, and 46.1% with nuclear reactors. On the other hand, in Sporckmann's study, about 6% of electricity was generated with oil, 7% with natural gas, 23% with coal, 7% with lignite, 19% with renewable sources, 36% with nuclear reactors, 1% with others. As a result, the impact of EV's on the atmosphere is more favorable in studies which utilize cleaner power plants such as hydroelectric and nuclear energy.

#### 2.4.1.1 EV's Energy Efficiency

To carry out environmental studies it is necessary to quantify the emission associated with EV's in order to estimate net emission benefits. Then, it is important to be familiar with the efficiencies of power plants and their air pollution inventories. Also, it is necessary to determine the total energy consumed by EV's. That is, the energy efficiency of electric vehicles (kWh/km) has to be known as does the average daily miles traveled (km). With this information, it is possible to determine the amount of energy directly consumed by an EV. However, it is also necessary to consider the charger's efficiency in order to determine the total energy consumed. Although most of the previously mentioned studies considered battery chargers efficiency (around 70%), there were studies such as Morrow and Dekoster's (1994) that did not take this factors into account. Nevertheless, one of their assumptions that "EV efficiencies are based on technology expected to be available in two to five years... .75 kWh per mile for light trucks... .2 kWh per mile for cars..." might refer to the global efficiency of EV's including the battery charger efficiency.

It is uncertain what EV technologies will be available in the market. Current EV environmental studies also differ in the type of electric vehicles and battery characteristics analyzed. For example, Hayashi et al. (1994) considered six different EV's provided by Japanese electric power companies; four of these cars were R&D vehicles of which three used nickel cadmium and one used nickel zinc batteries; the other two cars were commercial vehicles with lead-acid batteries. Prakash et al. (1994) studied three different EV's, namely, G-van (lead-acid battery), Bedford van (nickel/cadmium battery), and Rocaboy van (lead acid battery), all of which have different energy efficiencies: 0.56, 0.40, 0.19 kWh/km respectively.

Other studies (Morrow and Dekoster 1994, Sporckmann 1994, Tenure 1994) considered predicted values of EV energy efficiencies based on technology expected to be available in the near future. Morrow and Dekoster (1994) assumed that EV efficiencies ranged from 0.470 kWh/km for light trucks in a low efficiency scenario to 0.125 kWh/km for cars in a high efficiency scenario. Sporckmann (1994) assumed that an electric passenger car had an efficiency of 0.222 kWh/km. Turner (1994) analyzed near-term energy efficiencies of five EV's , namely, Conceptor G-Van (0.746 kWh/km), Chrysler TEVan (0.274 kWh/km), Solectria (0.156 kWh/km), Ford Ecostar (0.218 kWh/km), and GM Impact (0.087 kWh/km); with the exception of the G-Van's efficiency, which was based on actual field use, the EV energy efficiencies were manufacturer claims, based on controlled tests. In his analysis, Tenure assumed that EV's would have the efficiencies shown in Table 2.9.

Wenger and Chang (1994) listed the different values of EV energy efficiencies used in analyses performed by the California Air Resource Board (ARB), the Natural Resource Defense Council/Environmental Defense Fund (NRDC/EDF), and the Electric

Power Research Institute (EPRI). The energy efficiency values used by the ARB ranged from 0.15 to 0.22 kWh/km, while those of the NRDC/EDF ranged from 0.132 to 0.294 kWh. The energy efficiency used by EPRI was 0.16 kWh/km.

**2.4.1.2 Factors That Affect EV's Energy Efficiency**

The variations in energy efficiencies used in EV environmental studies are not only due to the type of electric vehicle and battery technology but also to predominant topographic characteristics, whether conditions, and traffic patterns of the region or city studied. Hayashi et al. (1994) carried out a test to determine the efficiency of EV's in actual driving conditions. They found that running conditions, such as whether the road is sloping, whether it is surfaced with snow, and whether subsidiary equipment such as air conditioners are used, greatly impact EV's energy consumption.

Prakash et al. (1994) reported that a dynamometer test on the G-van showed a decrease of about 75.8% in the driving distance in going from room temperature to -20 C. In addition, an average 52% drop in the overall efficiency of the G-van to an average of 0.85 km/kWh at -20 C was shown. Prakash et al. said that "this decrease is due to the cold temperature causing a decrease in electrolyte conductivity which results in increased internal resistance and a decrease in the capacity of the battery pack." In addition, they reported that the decrease in overall energy efficiency is also a result of decreased rolling efficiency caused by the lubrication greases becoming more viscous at low temperatures.

Sperling (1994) indicated that EV energy efficiency is susceptible to extremely hot and cold temperatures since the use of heating and cooling systems in EV's reduces their

Table 2.9 EV Energy Efficiencies. (Turner, 1994).

| Vehicle Type | Year | | |
|---|---|---|---|
| | 2000 | 2005 | 2010 |
| Cars | 0.250 kWh/km | 0.218 kWh/km | 0.187 kWh/km |
| Light Trucks | 0.312 kWh/km | 0.281 kWh/km | 0.250 kWh/km |
| EV Fleet Average* | 0.271 kWh/km | 0.237 kWh/km | 0.200 kWh/km |

* Assumed a vehicle mix of 60% passenger cars and 40% of light trucks in 2000, changing to 80% passenger cars and 20% light trucks by 2010.

efficiencies significantly. Sperling explained that heating and cooling systems are not a problem in ICV's because they can draw on waste heat and surplus power from the engine; in contrast, EV motors do not generate enough heat to warm the cabin, nor do they store enough energy for conventional heating and cooling. "An EV using the same type of air conditioner and heater as an ICE would lose 20 percent of its range or more." (Sperling 1994).

Baba, Ishitani, and Matsuhashi (1994) found that in hilly course, the effects of altitude change or existence of slope is very significant. They stated that insufficient regenerating ability results in significant deterioration of energy efficiency. Quantitatively, they determined that when there exists 200 m up-down in a 5.8 km course, the energy efficiency would be decreased by about 30 to 40%.

**2.4.1.3 EV's Environmental Studies Results**

Even though there were a number of differences in the types of power plants and primary energy used in each study, and a variety of assumptions about EV energy efficiency values, overall efficiencies of electric systems, driving conditions, and traffic patterns, all the studies found a positive impact of EV's on the atmosphere. Wenger and Chang (1994) presented the results obtained by the ARB' analysis for the South Coast Air Basin (SCAB) and compared them with the results obtained by the NRDC/EDF, EPRI, and the emissions from an average vehicle on the road in California in 1994. The pollutants analyzed were oxides of nitrogen ($NO_x$), reactive organic gas (ROG), and carbon monoxide (CO). The amount of pollution was expressed in kilograms per 160,900-kilometer life. These results are shown in Table 2.10 where it can be seen that if an ICV is replaced by an EV the reduction of emissions of each kind of pollutant analyzed is significant.

Sporckmann (1994) reported the predicted global air pollutant emissions of passenger cars in Europe, shown in Figure 2.3. Sporckmann said that the results of the comparisons of air pollutant emissions for the year 1992 show the great advantage of EV's, taken on an average European basis. He concluded that at the global level all the pollutants of electric vehicles except sulphur dioxide are much less than the emissions of IC vehicles.

Prakash et al. (1994) found that the emission profile for the three vehicles analyzed (G-van, Bedford van, and Rocaboy van) was significantly less than that of a gasoline powered vehicle, except for the level of sulfur dioxide ($SO_2$) which was greater for the electric vehicle as can be seen in Table 2.11. They explained that the high level of $SO_2$ results from the burning of coal and oil at power stations, while the gasoline refining process removes the sulfur which prevents it from being emitted into the atmosphere. Prakash et al. concluded that EV's were less polluting than ICV's and would have a net beneficial effect by reducing the cost to society caused by fossil fuel generated emissions.

Hayashi et al. (1994) compared the emission caused by a conventional vehicle and six EV's which were called A, B, C, D, E, and F (A, B, C, and D were R &D electric vehicles, and D and F were commercial EV's). For this comparison, they considered the over all emissions involved in the electric generation process; for instance, they took into consideration refinery, transportation, power plant, and power distribution efficiencies as well as charger and vehicle efficiencies. For the gasoline-powered vehicle, they considered refinery, transportation, and gas-station efficiencies as well as vehicle efficiencies. The

Table 2.10 Comparison of Emissions Associated with EV's.
(Wenger and Chang, 1994).

(kilograms per 160,900-kilometer life)

| Scenario | $NO_x$ | ROG | CO |
|---|---|---|---|
| ARB | 0.59 | 0.082-0.10 | 0.91-1.0 |
| NRDC/EDF | 0.50-1.1 | 0.20-0.50 | 0.68-1.7 |
| EPRI | 1.3 | 0.40 | 2.5 |
| Gasoline ICV | 110 | 150 | 1000 |

Table 2.11 Comparison of Emission Profiles in Ontario.
(Prakash et al. 1994).

| Vehicle Type | Emission Profile (g/km) | | | | |
|---|---|---|---|---|---|
| | $CO_2$ | CO | $NO_x$ | HC | $SO_2$ |
| IC vehicle | 288.0 | 12.06 | 0.910 | 1.310 | 0 |
| G-van | 143.2 | 0.026 | 0.261 | 0.002 | 0.765 |
| Bedford van | 103.1 | 0.018 | 0.188 | 0.002 | 0.550 |
| Rocaboy van | 50.5 | 0.009 | 0.092 | 0.001 | 0.270 |

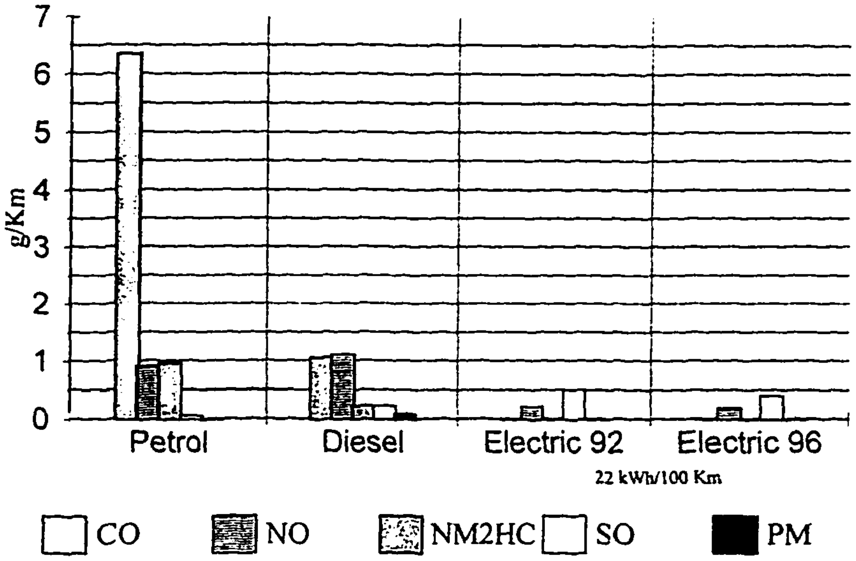


Figure 2.3 Global Air Pollution Emission of EV's in Europe.
(Sporckmann 1994, pg. 153).

results obtained for $CO_2$ and $NO_x$ emissions are shown in Figure 2.4 and 2.5 respectively. In these tables, it can be seen that there is a significant difference between the amount of pollutants emitted by EV's and those emitted by a gasoline powered vehicle. Hayashi et al. (1994) concluded that the results of this study "confirmed that the energy consumption rate and environment improvement effects are superior to those of petrol-based cars." However, they said that in actually installing and using EV's, matters such as cost, maintenance, and infrastructure improvements needed to be considered.

### 2.4.2 EV's Economic Issues

Most economic studies of EV's focus only on the direct costs of EV's (manufacturing costs including marketing plus profit). Generally, these costs refer to the market price or production costs. For instance, these costs include the cost of electric systems, batteries, electric motors, car body, etc. Many of the studies not only analyze the costs of the EV structural and functional parts but also study ways to minimize the costs and maximize the efficiency of EV's components (Spentzas, Koulocheris, and Jouralas 1994).

The final cost of an EV (direct cost or market price) is predicted to be paid by the customer in the long term. However, since there are many parties interested in introducing EV's into the market, the final cost of an EV is expected to be paid initially by the customer, manufacturer, utilities companies, and the government (Sperling 1994).

Additional costs include the EV operation costs which are usually assumed to be the costs of energy consumed by electric vehicles. Generally, these costs are determined by the EV energy efficiency (kWh/km), the EV daily average of miles traveled (km), and

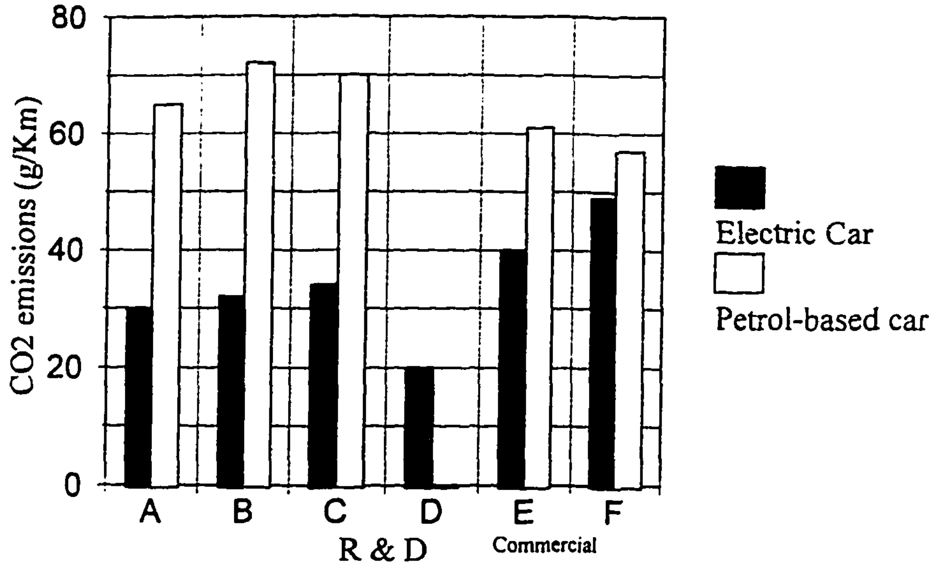


Figure 2.4 Carbon Dioxide Emission of EV's vs. an ICV.
(Hayashi et al. 1994, pg. 166).

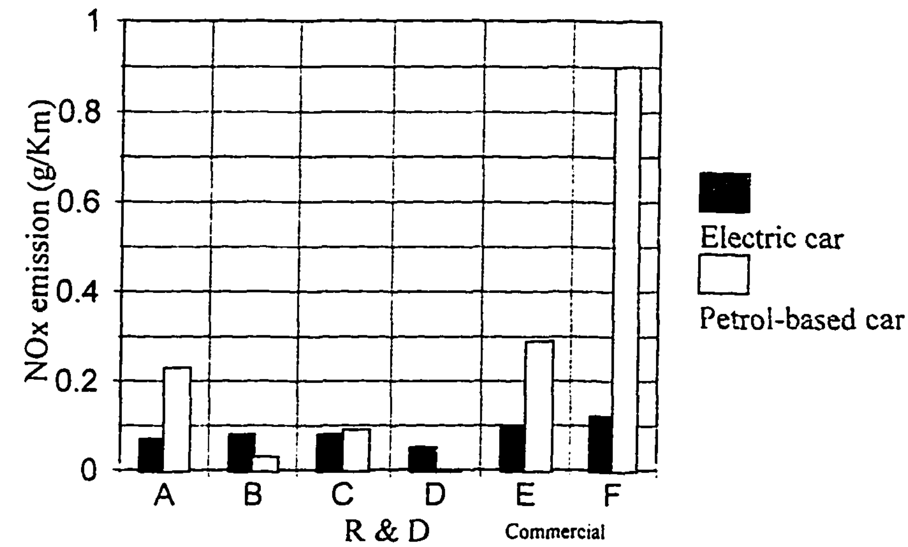


Figure 2.5 Nitrogen Oxides Emission of EV's vs. an ICV.
(Hayashi et al. 1994, pg. 167).

the price of the kWh ($/kWh) in the region studied. In most of the studies it is assumed that these costs will be paid by the EV owner.

There are also indirect costs of EV's which refer to the costs of the infrastructure required to make the use of electric vehicles practical. Basically, this infrastructure includes residential rechargers, special outlets, recharge centers, parking places with outlets to recharge EV's, electric transformers, and perhaps new electric power plants (Sperling 1995). Consequently, the main concern is the charging infrastructure and the economic impact of EV's on the electric system since the replacement of electric transformers and the expansion of electric plants are major infrastructural costs. Overall, most studies expect indirect costs to be paid by many parties, namely, utilities companies, building owners, EV's owners, EV's manufacturers, and the government.

Since direct costs are basically set by the manufacturer and operational costs are readily determined, the indirect costs, mainly, the impacts of EV's on the electric system and recharging infrastructure, have been the focus of many studies concerned with the overall impact of EV's in urban areas.

Owen, Simpson, and McGuire (1994) stated that the major barrier to introducing electric vehicles is the lack of fast charging infrastructure. This barrier is also linked to the high costs of present off-board charger/controllers affecting the complex charge process, and also to concerns that chargers could affect power quality. They said that the effects of battery charging could result in: "increased electricity system peak demands above available system capacity, reduced safety and life time costs of electricity system equipment, and more supply variation interruption interruptions to electricity consumers."

Even though consumer market research suggested that any widespread adoption of EV's would required fast charging points, it is often assumed that about 80% of EV recharging will be done at home because of preferential electricity tariffs (Owen et al. 1994)

Frost (1994) stated that EV loads can be divided into the following charging characteristics: residential, opportunity, commercial fleet, and quick charging, so that each charging category appears on the system at different power delivery levels. Frost pointed out that the "load occurring at the lower voltage power delivery levels is cumulative as we progress up the system from distribution to transmission levels." Therefore, studies are generally carried out by analyzing impacts at the following discrete levels: service and transformer, distribution circuit, substation transformer, subtransmission/receiving station, bulk transmission, and generation (Frost 1994).

Rice (1994) said that intensive use of EV's could have significant impact on a utility's electrical system infrastructure. He stated that "use of a single EV charger could potentially double a household's electrical demand" and that power quality could also be affected. In the residential case, this will take place at the service and transformer level.

Frost (1994) explained the effect of charging EV's on a typical 50 kVA serving eight residential customers. He found that the average peak load for residential customers is typically 7 kW and that, coincidently, 7 kW happens to be an estimate for a typical residential EV charger. He stated that "transformer sizing design criteria does not provide a lot of margin, certainly not for multiple 7 kW loads." In addition, if a specific area has multiple EV's, the chances of simultaneous charging increase; as a result, transformer voltage and thermal drop ratings would require evaluation. Frost concluded that without load control it is more likely that transformer replacement would be necessary. Finally, he said that the approximated cost for a transformer replacement is $3,750.

Rice (1994) pointed out that in order to prepare the infrastructure to serve the new load demanded by EV's, it would be necessary to make predictions about where and when the load would take place on the electric system. Consequently, predicting location and characteristics of EV load, and matching the information against distribution systems capabilities in specific parts of the electric system is critical to the process of implementing load-management strategies and upgrading system facilities, where necessary, so that the new EV load can be accommodated without negative impacts on the electric system (Rice 1994). The key aspects needed to determine the EV's impact on the system are magnitude, duration, location and timing of the load. In other words, it is necessary to know the number of EV's, the year they enter the system, the length of charging, and their location on the system (Frost 1994).

In order to reduce high initial investments, it is necessary to determine a program schedule to introduce EV's in such a way that the electric system will not be dramatically affected. Brown and Frost (1994) and Hayashi, Inasaki, and Anan (1994) found that overnight- managed residential charging has the least impact on electric systems. However, these studies were carried out considering information from specific regions. For instance, Brown and Foster used information from the metropolitan Phoenix area, and Hayashi et al. (1994a) based their study on data from a region in Japan. McShane, Mcguire, and Mead (1994) evaluated the use of conventional and advance battery charging technology on a specific utility feeder in a residential area. They found that advanced battery technology, not only delays the need for costly utility upgrading by maximizing the infrastructure capacity, but also gives the opportunity for demand side management and system load leveling to provide further utility advantages.

Kennedy (1994) stated that at this stage of technology there are many unknowns. For example, it is uncertain if the utility or the customer will be able to physically control the load and if the load will be controlled remotely by the utility or at the customer location. It is unknown what characteristics the commercial EV electric chargers will have, and what their price will be. Frost (1994) stated that the "system load requirements will vary as new technology emerges, as various charging infrastructure is installed and as load management measures are implemented." Therefore, EV environmental and economic analysis should be flexible to allow analysis of multiple scenarios. In addition, the cost of the introduction of EV's and the new infrastructure costs must be weighed against tangible revenue increases and intangible environmental benefits supporting EV development (Frost 1994).

# CHAPTER 3

# METHODOLOGY

This chapter presents the methodology used to calculate the marginal cost of introducing electric vehicles (EV's) into a metropolitan area and to determine the reduction of emissions and the benefits from substituting EV's for conventional vehicles over a given period of time. With the output of this model, it is possible to calculate the reduction of emissions per dollar invested in EV's.

In order to carry out the cost analysis and determine the air pollution impact of introducing electric vehicles (EV's) into a metropolitan area, the topography, climate, infrastructure, and traffic conditions of Mexico City and its Metropolitan Area (MCMA) are considered. Since each metropolitan area has specific characteristics such as climate, infrastructure and traffic conditions, a flexible model that can be adjusted to other metropolises without significant changes was designed. The general approach of this study is described as follows:

- First, the changes of vehicle characteristics caused by the introduction of EV's is simulated (as described in Section 3.3.1); within this section, the number and type of vehicles and their age distribution per year is determined.
- Second, based on the data obtained from the previous step, the direct cost of EV's, the marginal demand of electricity, the operational costs of EV's , and the overall cost of EV's per year is determined (as explained in Section 3.3.2, 3.3.3, 3.3.4, and 3.3.5, respectively).

- Third, the costs of internal combustion vehicles (ICV's) per year are calculated (based on the equations described in Section 3.3.6).
- Fourth, after the EV's and ICV's costs are determined the marginal costs of introducing EV's per year are calculated (Section 3.3.7).
- Fifth, in order to determine the total emissions in the system per year the total number of miles traveled per year by the remaining ICV's in the system are determined (Section 3.3.8).
- Sixth, using the information generated in the first step (Section 3.3.1) and the characteristics of the metropolitan area, the emission factors of hydrocarbon (HC), carbon monoxide (CO), and nitrogen oxides ($NO_x$) are determined. The emission factors are calculated with MOBILE5, a software package used by the U.S. Environmental Protection Agency (EPA) to determine emission factors of mobile sources. After the emission factors are determined, the total emissions generated by ICV's are determined (Section 3.3.9).
- Seventh, the total reduction of each pollutant, HC, CO, and $NO_x$, is determined. Then, the impact on the air quality (concentration of ozone) is estimated using the emission-concentration relations for MCMA found by the Los Alamos National Laboratory and the "Instituto Mexicano de Petroleos" in 1994 (Section 3.3.10).
- Eighth, the benefits from introducing EV's and replacing conventional vehicles with EV's are determined (Section 3.3.11).

The model developed in this study is a simulation program written in FORTRAN. A simulation model is an experimental and applied methodology that seeks to describe the behavior of a system, construct theories that account for the observed behavior, and predict future behavior, i.e., the effects produced by changes in the system or in its method of operation (Pegden, Shannon, and Sadowski 1990). This simulation model is flexible; for instance, if parameters such as vehicle deterioration rate, EV's prices, battery prices, battery recharger efficiency, vehicles demand, and electricity prices change, the model can be readily modified and adjusted to the new parameters or conditions.

This simulation model requires specific data (input) which are interrelated (process) in order to obtain the required results (output). To carry out the simulation study the following six steps were taken. First, the goal or purpose of the simulation model was defined (Section 3.1). Second, the boundaries of the system were defined and assumptions were made (Section 3.2). Third, a conceptual model was formulated and translated into a simulation programming language (Section 3.3). Fourth, the input data were collected and analyzed (Section 3.4). Fifth, the program was verified and validated (Section 3.5 and 3.6). Sixth, an experiment which considers different scenarios was carried out and the results were analyzed; this latter point is covered with more detail in Chapter 4.

### 3.1 Definition of Goals

The goal of this study is to simulate the effects of introducing EV's into a metropolitan area, calculate the marginal cost of introducing these vehicles into the system, and determine the reduction of emissions and the benefits caused by EV's over a specified period of time. Consequently, the simulation model provides the following information:

1) Total number of vehicles in the system in a given year.

2) Number of EV's in the system per year.

3) Number of conventional vehicles remaining in the system per year.

4) EV's marginal cost ($/year).

5) Total vehicle miles traveled per year (miles/year).

6) MOBILE input files to determine emissions per year.

7) Reduction of emissions and their impact on air quality.

8) Benefits from introducing EV's.

In order to accomplish the goals of this study, five different scenarios were analyzed, namely, low introduction rate scenario (LIRS), moderate introduction rate scenario (MIRS), high introduction rate scenario (HIRS), no action taken scenario (NATS) and forced retirement scenario (FRTS); these scenarios are described as follows:

**Low Introduction Rate Scenario (LIRS).** The introduction rate of this scenario is determined based on a normal vehicle growth rate and deterioration rate. In this scenario, a given percentage of the normally replaced vehicles (ICV-ICV replacement) and certain percentage of the additional vehicles introduced into the system per year are electric vehicles. This is the case when there is only a small number of EV's in the new car market compared to that of internal combustion vehicles (ICV's). The percentage of vehicles in the market per year depends on a program similar to the 1990 Zero Emission Vehicle (ZEV) law from California. The schedule used in this study is the following:

| | | |
|---|---|---|
| From year: | 2000 to end of 2002, | 2% of the new vehicles are EV's |
| | 2003 to end of 2004, | 5% of the new vehicles are EV's |
| | 2005 to end of 2006, | 10% of the new vehicles are EV's |
| | 2007 to end of 2008, | 15% of the new vehicles are EV's |
| | 2009 to end of 2009, | 20% of the new vehicles are EV's |
| | 2010 to end of 2010, | 25% of the new vehicles are EV's |

The percentage continues to increase by 5% per year until year 2020.

**Moderate Introduction Rate Scenario (MIRS).** The introduction rate of this scenario is determined based on a normal vehicle growth and deterioration rate as in the LIRS. However, in this scenario, MIRS, all the normally replaced vehicles (ICV-ICV replacement) and all additional vehicles introduced per year because of growth are electric vehicles. This is the case when an emergency plan to reduce air pollution emissions is implemented and no internal combustion vehicles are sold for private use.

**High Introduction Rate Scenario (HIRS).** The introduction rate of this scenario is determined based on a normal vehicular growth rate and an imposed replacement program. In this scenario, all the vehicles introduced per year are electric vehicles. This is the case when a governmental emergency plan to reduce air pollution is introduced. This plan establishes that at the beginning of the year 2000, the oldest vehicles in the system have to be replaced with EV's. The schedule proposed by this plan is the following:

| Year | Replaced |
|---|---|
| 2000 | 25 year old ICV's and older |
| 2001 | 24-year old ICV's and older |

| | |
|---|---|
| 2002 | 23-year old ICV's and older |
| 2003 | 22-year old ICV's and older |
| ... | ...... |
| 2014 | 15-year old ICV's and older |

Note: after year 2014 no ICV's older than 15 years will be in the system.

**No Action Taken Scenario (NATS).** This scenario simulates the effects of conventional vehicles on air pollution from the year 2000 to year 2020. In this scenario, there will be no introduction of EV's. Basically, this scenario represents the ICV's expected air pollution contribution if additional pollution control programs are not implemented. This scenario is used as a reference point to compare the effects of the other scenarios.

**Forced Retirement Scenario (FRTS).** This scenario is similar to the high introduction rate scenario (HIRS); however, in this scenario, all the new vehicles introduced are internal combustion vehicles. This scenario assumes that there is no introduction of EV's. The schedule used to retire vehicles from the system is the same as the schedule used in the HIRS.

The model is capable of analyzing other types of scenarios without changing its structure. For instance, other scenarios that may consider different EV's introduction rates can be simulated by simply updating the information and introducing the new schedule into the input file of the model. For scenarios that include vehicles other than private gasoline-powered ICV's and EV's, structural changes to the model may be required.

## 3.2 System Definition and Assumptions

### 3.2.1 System Definition

The main boundaries and restrictions of the model representing the system are the following: the geographical area of study, Mexico City and its Metropolitan Area: the emissions generated only by the transportation system. particularly. private cars (gasoline-powered vehicles); and the current number of vehicles in the transportation system. Other specific restrictions are the type of electric vehicles in the market and the type of pollutants analyzed. This study considers three type of vehicles, namely, two-passenger vehicles, four-passenger vehicles and mini-vans. The pollutants considered are hydrocarbons (HC). carbon monoxide (CO), nitrogen oxides ($NO_x$), and ozone which are the main pollutants emitted by gasoline-powered vehicles, except for ozone which is formed by a chemical reaction of HC, $NO_x$, and sunlight.

### 3.2.2 Assumptions

Assumptions that are considered in this study are listed as follows:

<u>Assumptions about vehicles</u>:

1) Only the three most common types of EV's designed for urban areas are considered. namely. two passenger vehicles, four passenger vehicles, and mini vans. None of these EV's will be equipped with air conditioning and heating systems which are considered luxury features since they are not needed due to the favorable climate of Mexico City and its Metropolitan Area.
2) The percentage of two-passenger EV's introduced corresponds to the percentage of subcompact and sport cars sold in recent years; the percentage of four passenger

EV's corresponds to the percentage of compact and luxury cars; and the percentage of EV mini vans corresponds to the percentage of certain types of vans and trucks sold in the same period in Mexico City. The percentages of each type of vehicles are obtained from the AMIA (Mexican Association of the Automobile Industry).

3) Depending on the scenario, the additional vehicles in the system are brand new ICV's or EV's and all the replaced vehicles are substituted for new ICV's or EV's. That is, used vehicles from outside of Mexico City and its Metropolitan Area will not be introduced into the transportation system of MCMA.

4) Although it is expected that EV's will have less mechanical failures and longer life than ICV's, it is assumed that EV's deterioration rate is the same to the deterioration rate of ICV's. This assumption is made due because there is no historical information about the deterioration rate of EV's of different ages under real life conditions. The deterioration rates are determined based on the ICV's age distribution in MCMA reported by the government of Mexico City (DDF 1996)

5) The normal deterioration rate of conventional vehicles is constant over the time; for instance, if the deterioration rates of vehicles of two and three years of age are 0.97 and 0.95 in year 2000, respectively, these rates will be the same for all vehicles of two and three years of age from year 2001 to 2020, respectively.

6) The 1993 vehicle age distribution is the same distribution at the beginning of the study, year 2000. In general, under stable conditions, when only the same types of vehicles (ICV's) are being introduced into the system at normal introduction rates,

the age distribution of the vehicles in the system is approximately the same over a given period of time (EPA 1994).

7) Vehicles older than 25 years are considered as 25-year old vehicles. This assumption is made due to the restrictions of MOBILE5, a software package used by the U.S. Environmental Protection Agency (EPA), the government of Mexico, and this study to determine emissions factors of mobile sources. In order to determine the emission factors, MOBILE5 considers vehicles from age 1 (new vehicles) to vehicles of age 25 (EPA 1994).

8) The average distance traveled by EV's is the same distance that internal combustion vehicles travel within the city.

9) The average efficiency (km/L) of ICV's is determined based on vehicles from current years since commercial ICV's efficiencies for the future are not known with certainty.

<u>Assumptions about electricity and economy</u>:

1) Since Mexico City is importing most of its energy from other states, it is assumed that all the electricity consumed in MCMA is generated by power plants located out of the metropolitan area. The two natural gas power plants in MCMA are working close to their maximum capacity which is relatively small (INEGI 1993).

2) The demand for electricity by EV's takes place during off-peak time. That is, the EV's batteries are recharged at night from midnight to 6:00 A.M. During this time, the electricity demand is low.

3) It is assumed that the expansion of power plants and the installation of new substations are treated as a new investment by the utility company. The company will recover its investment and obtain a profit by increasing the utilization of their plants and selling more energy to its customers. As a result, the cost of power plants and substation expansion is not considered as a part of the overall cost of introducing EV's.

4) It is assumed that the economy is stable and there is a perfect capital market. The type of currency used is 1996 US dollars.

### 3.3 Conceptual Model Formulation and Model Translation

Within this step, a preliminary model was developed first. The model was represented graphically and in pseudo-code to define the components, descriptive variables, and logic or interactions that constitute the system.

In order to develop the preliminary model, the pertinent components of the system were identified. This process itemized all system components that contribute to the effectiveness or ineffectiveness of its operation (brain storming process). After a complete list of components was specified, it was necessary to determine what components should be included in the model. After the preliminary model was developed the appropriate elements were identified and the functional relationship among them was determined.

To analyze the elements of the system and select the appropriate components (constraints and parameters) of the simulation model, the information was classified in four groups: 1) electric vehicles, 2) utility companies, 3) conventional vehicles, and 4) air quality. Within each of these groups. pertinent elements related with the direct effects on air pollution and costs were identified. These elements are listed as follows:

1) Electric vehicles information:

Traffic patterns: Number of hours traveled per day or average miles per day, number of people traveling per car. and road conditions. (Sources of information: the Department of Vehicles of Mexico City).

Type of EV's: Vehicle characteristics, car or van, passenger capacity, kind of battery, battery cost, EV's efficiency (kWh/km), and cost of vehicles. (Sources: EV's proceedings and manufacturer reports).

Battery recharger: Type of rechargers and their efficiency, location of rechargers, and recharger cost. (Sources: EV's proceedings and manufacturer reports).

Expected sales: Number and type of vehicles sold per year and expected replacement rate. (Sources: the Department of Vehicles of Mexico City, the Mexican Association of the Automobile Industry, and the American Embassy).

2) Utilities Companies Information:

Power plants: Number of power plants, type of plants, type of primary energy used, plants capacities, plants efficiencies, plants emissions (kg/kWh), and cost of expansion. (Source: Mexican Utility Company, and the National Institute of Statistics, Geography and Information, INEGI)

Transformers: Number of transformers, location, capacity, and cost of expansion. (Source: Utility Company)

Electricity Demand: Electricity prices, average of kWh demanded, and peak hours of power plants. (Source: Utility Company)

3) Conventional Vehicles Information:

Type of ICV's: Number of ICV's to be replaced, cost of vehicles, efficiency, energy consumption (L/km), tail pipe emissions, fuel price, and operation and maintenance. (Sources: the Department of Vehicles of Mexico City, the Department of Environmental Protection of Mexico, and the American Embassy).

4) Environmental Conditions:

Air Quality: Type of pollutants, emissions, concentrations, permissible limits, and sources of emissions. (Sources: the Department of Environmental Protection of Mexico, and the World Health Organization).

The relationship among most of these elements was presented graphically and in pseudo-code. Figure 3.1 presents a flow chart that represents the procedure to determine the relation among the elements that influence the reduction of emissions and the overall cost of introducing EV's into the system.

Before presenting the model in pseudo-code, names were assigned to variables and parameters as shown in the following list:

| | |
|---|---|
| AGEE= | EV's age distribution. |
| AGEI= | ICV's age distribution. |
| AMCY= | ICV's average maintenance cost per year. |
| BCOT= | Battery charger, outlet, and transformer costs. |
| BTPR= | Battery prices. |
| BTLF= | Battery lives. |
| DCEV= | Direct cost of EV's introduced in current year. |
| EDPY= | Energy demanded by the EV's introduced in current year. |
| EFBC= | Battery charger efficiency. |
| EVDR= | EV's deterioration rate. |
| EVADT= | EV's average distances traveled per year. |
| EVEFF= | EV's efficiencies. |
| EVMK= | EV's market share. |
| EVSA= | Number of EV's of each age in current year. |
| GASP= | Gasoline price. |
| ICDR= | ICV's deterioration rate. |
| ICEFF= | ICV's efficiencies. |
| ICVA= | Number of ICV's of each age in current year. |
| ICVC= | ICV's cumulative overall cost in current year. |
| MCEV= | EV's cumulative marginal cost. |
| NETYP= | Number of EV's of each type introduced in current year. |
| NEVY= | Number of EV's introduced in current year. |
| NICY= | Number of ICV's introduced in current year. |
| NITYP= | Number of ICV's of each type introduced in current year. |
| OPCT= | EV's cumulative operational costs in current year. |
| OVCT= | EV's cumulative overall cost in current year. |
| PRECV= | EV's prices. |
| PREL= | Price of electricity. |
| PRICV= | ICV's prices. |
| PVTYP= | Percentage of each type of vehicles in the system. |
| RVAGE= | Remaining ICV's age distribution. |
| TDCV= | EV's cumulative direct cost in current year. |
| TEDS= | Total energy demanded by all EV's in the system. |
| TETYP= | Total number of EV's of each type in current year. |
| TNEV = | Total number of EV's in the system in current year. |
| TITYP= | Total number of ICV's of each type in current year. |
| TIME= | Current year. |
| TNIC= | Total number of ICV's in the system in current year. |
| TNVS= | Total number of vehicles in the system. |
| TYPE= | Number of EV's types. |
| TVMT= | Total vehicles miles traveled. |
| VGRT= | Vehicle growth rate. |

After the names of variables and parameters were assigned, the preliminary model was written in pseudo-code as follows:

1) Introduced input data.
2) Determine number of cars arriving into the system per year (TNVS).
3) Calculate number of vehicles of each type, 2 passenger, 4 passenger and mini-van. entering the system (NEVY, NICY, NETYP and NITYP).
4) Determine direct cost of new EV's (DCEV).
5) Calculate EV's energy demand (EDPY and TEDS ).
6) Determine operational cost of electric vehicles (OPCT).
7) Determine overall cost of EV's (OVCT).
8) Calculate ICV's related costs (ICVC).
9) Determine EV's marginal cost (MCEV)
10) Create MOBILE input data.
11) Determine emission factors (MOBILE5)
12) Determine emissions caused by ICV's remaining in the system.
13) Determine the reduction of emissions per year.
14) Determine effects on air quality.
15) Estimate EV's benefits of reducing air pollution.
16) Compare total benefits and marginal cost of EV's.
17) Print results.

In order to formulate the model, the general steps listed in pseudo-code were followed. Most of the formulation is presented in the order shown in the methodology flow chart, Figure 3.1. The first point, "Input Data", is discussed in section 3.4. The results are presented in Chapter 4 and Appendix B.

### 3.3.1 Vehicle Dynamics

In this section, the equations to determine the number and type of electric vehicles introduced into the system as well as the procedure to determine the ICV's age distribution are developed. The number of cars introduced per year depend on the scenario that is analyzed, namely, low introduction rate (LIRS), moderate introduction rate (MIRS), high introduction rate (HIRS), no action taken (NATS), and force retirement scenarios (FRTS).

Assumptions:

1) Depending on the type of scenario, the additional vehicles in the system are brand new ICV's or EV's and all the replaced vehicles are replaced with new ICV's or EV's.
2) EV's deterioration rate is the same as the deterioration rate of ICV's.
3) Vehicles older than 25 years are considered as 25 year old vehicles.

In order to determine the number of EV's introduced in a given year, the number of remaining ICV's in the system, and the ICV's age distribution, the following steps are carried out:

1. The total number of vehicles that are expected to be in the system in a given year is determined with the following equation:

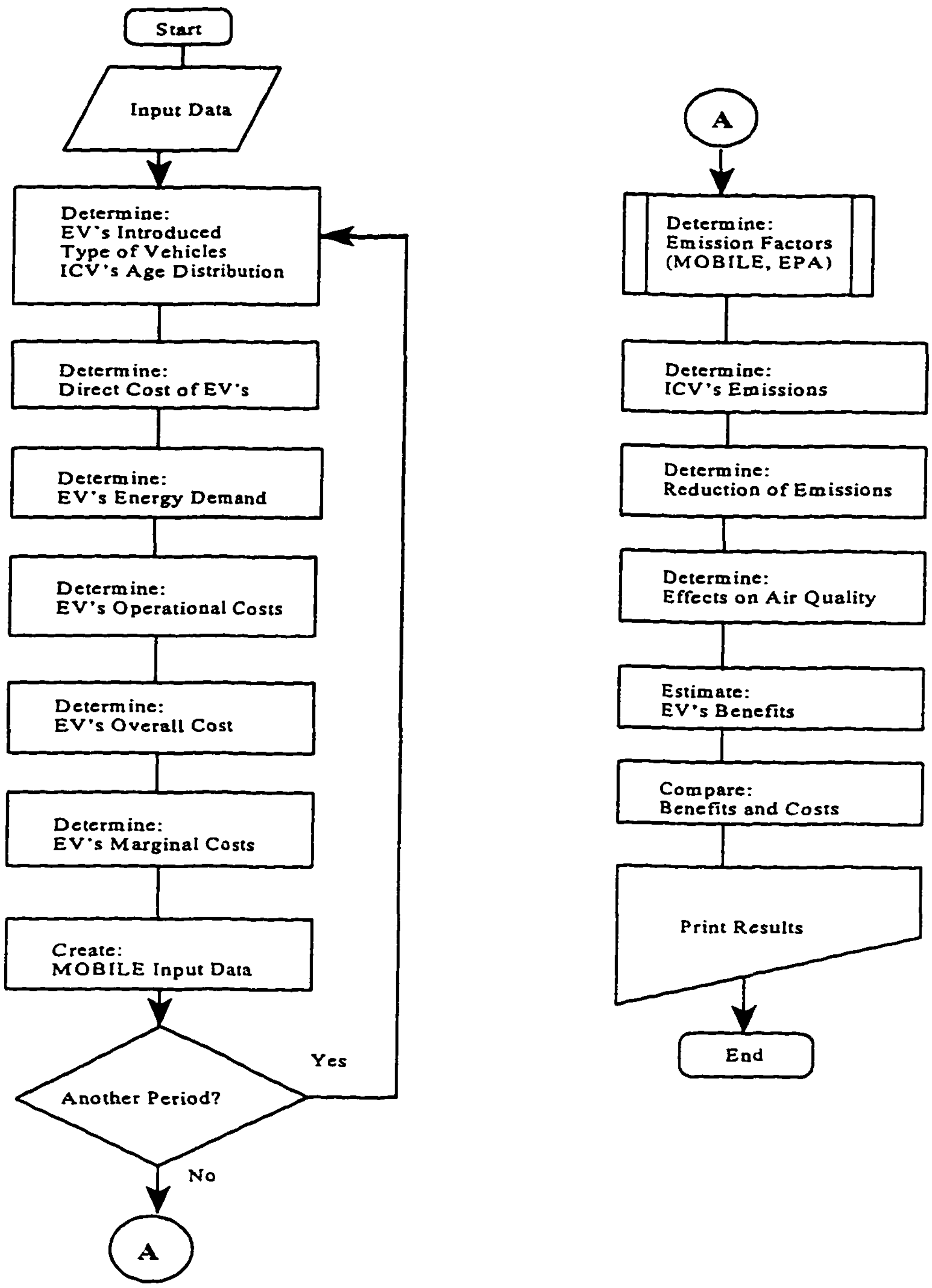


Figure 3.1 Methodology Flow Chart.

$$TNVS_i = [TNVS_{i-1}] * [1 + VGRT] \tag{3.1}$$

where:

TNVS= Total number of vehicles expected to be in year i.
VGRT= Vehicle Growth Rate.

2. The number of ICV's and EV's that remain in the system after one year of circulation are determined with equations (3.2) and (3.3), respectively. In order to determine the number of vehicles remaining at the beginning of a new year, the number of vehicles from the previous year is multiplied by the deterioration rate which varies according to the age of each vehicle:

from k =1 to k = 24,

$$ICAD_{i,\ k+1} = [ICVA_{i-1,\ k}] * [ICDR_k] \tag{3.2}$$

$$EVAD_{i,k+1} = [EVSA_{i-1,k}] * [EVDR_k] \tag{3.3}$$

where:

ICAD= Number of ICV's of age k after deterioration in year i.
ICVA= Number of ICV's of age k in year i.
ICDR= Deterioration rate of ICV's of age k.
EVAD= Number of EV's of age k after deterioration in year i.
EVSA= Number of EV's of age k in year i.
EVDR= Deterioration rate of EV's of age k.

For all scenarios the vehicle deterioration rates are constant except for the high introduction rate and the forced retirement scenarios. In these two scenarios, the deterioration rate for the oldest vehicles is one that makes that the number of ICV's of certain age become zero. For instance, in year 2000, the value of the deterioration rate

(ICDR) for all 25-year old ICV's will be equal to zero, in year 2001, the deterioration rate for vehicles of age 24 and older will be equal to zero, and so on until the oldest vehicles in the system are 15 years old.

During the transition phase, there are no vehicles of age zero. That is, all the vehicles have become one year older and no new vehicles have been introduced. Consequently, the values of ICAD and EVAD when $k = 1$ are zero. After determining the number of ICV's and EV's of each age after deterioration, the total number of ICV's and EV's in the system is calculated by adding the ICV's and EV's of each age as indicated in equation (3.4) and (3.5), respectively.

$$TICD_i = \sum_{K=1}^{25} ICAD_{i,k} \tag{3.4}$$

$$TEVD_i = \sum_{K=1}^{25} EVAD_{i,k} \tag{3.5}$$

where:

TICD= Total number of ICV's in the system after deterioration in year i.
ICAD= Number of ICV's of age k after deterioration in year i.
TEVD= Total number of EV's in the system after deterioration in year i.
EVAD= Number of EV's of age k after deterioration in year i.

3. The number of vehicles that has to be introduced into the system to satisfy the growth of vehicles and to recover the number of vehicles that have been lost because of the deterioration is determined by subtracting the total number of ICV's and EV's after

deterioration (TICD and TEVD) from the total number of vehicles required in the system for the new year (TNVS). This procedure is represented with equation (3.6).

$$NVIN_i = TNVS_i - TICD_i - TEVD_i \tag{3.6}$$

where:

NVIN= Number of vehicles introduced in year i.
TNVS= Total number of vehicles expected for year i.
TICD= Total number of ICV's in the system after deterioration in year i.
TEVD= Total number of EV's in the system after deterioration in year i.

After calculating the number of vehicles that have to be introduced in a given year (NVIN), the number of new EV's that will be introduced in that year (NEVY) is determined by multiplying the total number of vehicles to be introduced by the percentage of EV's in the new vehicle market for that specific year. This relation is mathematically represented with equation (3.7).

$$NEVY_i = [NVIN_i] * [EVMK_i] \tag{3.7}$$

where:

NEVY= Number of EV's introduced into the system in year i
NVIN= Number of vehicles introduced in year i.
EVMK= Percentage of EV's in the market of new vehicles.

For each scenario EVMK is different. For instance, the introduction of EV's in the low introduction rate scenario is different in every year since the percentage of EV's in the new vehicle market varies according to a schedule similar to the 1990 ZEV law from California, as explained in section 3.1. For the moderate introduction rate and the high introduction rate scenarios, the value of EVMK is 1 since 100% of the new vehicles introduced into the system are EV's. For the no action taken and the forced retirement scenarios, the value of EVMK is equal to zero since there is no introduction of EV's.

The number of new ICV's that will be introduced in a given year (NICY) is determined based on the percentage of EV's in the new vehicle market and the total number of vehicles to be introduced in that year (NVIN). The percentage of new ICV's to be introduced is calculated by subtracting the percentage of EV's from one since the total number of new ICV's plus the total number of new EV's are the total number of new vehicles in the system, 100%. This procedure is represented with equation (3.8)

$$NICY_i = [NVIN_i] * [1 - EVMK_i] \tag{3.8}$$

where:

NICY= Number of ICV's introduced into the system in year i
NVIN= Number of vehicles introduced in year i.
EVMK= Percentage of EV's in the new vehicle market.

4. The number of EV's of each age and the total number of EV's in the system in a given year are calculated as follows: first, the number of EV's of specific age in year *i* is determined with equation (3.9) and (3.10). Since the number of new EV's introduced in a given year (NEVY) is equal to the number of EV's of age one ($EVSA_{i,1}$), equation (3.9) equalized these two terms.

$$EVSA_{i,1} = NEVY_i \tag{3.9}$$

where:

EVSA= Number of EV's of age k (which in this case, k=1).
NEVY= Number of EV's introduced into the system in year i.

The numbers of EV's older than age 1 are determined by equalizing these numbers of vehicles of each age (EVSA) to the numbers of vehicles after deterioration (EVAD), respectively, as indicated in equation (3.10).

from k = 2 to 25,

$$EVSA_{i,k} = EVAD_{i,k} \tag{3.10}$$

where:

EVSA= Number of EV's of age k in year i.
EVAD= Number of EV's of age k after deterioration in year i.

Then, the total number of EV's in the system in a given year is calculated by adding the number of EV's of each age in that year as indicated in equation (3.11):

$$TNEV_i = \sum_{k=1}^{25} EVSA_{i,k} \tag{3.11}$$

where:

TNEV= Total number of EV's in the system in year i.
EVSA= Number of EV's of age k in year i.

6. The number of ICV's of each age and the total number of ICV's in the system in a given year is calculated using the same procedure applied for EV's. First, the number of ICV's of specific age in a given year is determined with equations (3.12) and (3.13). Since the number of new ICV's introduced in a given year (NICY) is equal to the number of ICV's of age one ($ICVA_{i,1}$), equation (3.12) equalized these two terms.

$$ICVA_{i,1} = NICY_i \tag{3.12}$$

where:

ICVA= Number of ICV's of age k (which in this case, k=1).
NICY= Number of EV's introduced into the system in year i.

The numbers of ICV's older than age 1 are determined by equalizing the numbers of vehicles of each age (ICVA) to the numbers of vehicles of each age after deterioration (ICAD), respectively, as indicated in equation (3.13).

from k = 2 to 25,

$$ICVA_{i,k} = ICAD_{i,k} \tag{3.13}$$

Then, the total number of ICV's in the system in a given year is calculated by adding the number of EV's of each age as indicated in equation (3.11):

$$TNIC_i = \sum_{k=1}^{25} ICVA_{i,k} \tag{3.14}$$

where:

TNIC= Total number of ICV's in the system in year i.
ICVA= Number of ICV's of age k in year i.

7. The distribution ages of ICV's and EV's in percentages are determined by dividing the number of ICV's and EV's of each age (ICVA and EVSA) by the total number of ICV's and EV's in a given year, respectively. Equation (3.15) and (3.16) are used to determine the age distribution of ICV's (AGEI) and EV's (AGEV) in a given year, respectively.

from k = 1 to 25,

$$AGEI_{i,k} = \frac{ICVA_{i,k}}{TNIC_i} \tag{3.15}$$

$$AGEE_{i,k} = \frac{EVSA_{i,k}}{TNEV_i} \tag{3.16}$$

where:

AGEI= ICV's age distribution in year i.
ICVA= Total number of ICV's of age k in year i.
TNIC= Total number of ICV's in year i.
AGEE= EV's age distribution in year i.
EVSA= Number of EV's of age k in year i.
TNEV= Total number of EV's in year i.

8. The number of vehicles of each type is determined based on the distribution of current vehicles in Mexico City. For instance, the percentage of two-passenger EV's introduced corresponds to the percentage of subcompact and sport cars sold in recent years; the percentage of four-passenger EV's corresponds to the percentage of compact and luxury cars; and the percentage of EV mini-vans correspond to the percentage of vans and light duty trucks sold in the same period in Mexico City. Although this study considers private vehicles only, the formulas developed in this section can be used to analyze other types of vehicles such as two-passenger EV taxis, four-passenger EV taxis, and EV taxi mini-vans. In order to determine the number of vehicles of each type introduced per year, the number of EV's and ICV's introduced into the system are multiplied by the percentage of each type of vehicles, as indicated in equation (3.17) and (3.18).

$$NETYP_{j,i} = [PVTYP_j] * [NEVY_i] \tag{3.17}$$

$$NITYP_{j,i} = [PVTYP_j] * [NICY_i] \tag{3.18}$$

where:

NETYP= Number of EV's of type j introduced in year i.
PVTYP= Percentage of vehicles of type j.
NEVY= Number of EV's introduced in year i.
NITYP= Number of ICV's of type j introduced in year i.
NICY= Number of ICV's introduced in year i.

The total number of EV's and ICV's of each type in a given year are determined by multiplying the total number of EV's and ICV's in the system in that year by the percentage of each type of vehicles, as indicated in equations (3.19) and (3.20).

$$TETYP_{j,i} = [PVTYP_j] * [TNEV_i] \tag{3.19}$$

$$TITYP_{j,i} = [PVTYP_j] * [TNIC_i] \tag{3.20}$$

where:

TETYP= Total number of EV's of type j in year i.
PVTYP= Percentage of vehicles of type j.
TNEV= Total number of EV's in year i.
TITYP= Total number of ICV's of type j in year i.
TNIC= Total number of ICV's in year i.

### 3.3.2 Direct Cost of EV's

In this section, the formula to determine the direct cost of electric vehicles is developed. The price of vehicles varies depending on the type of vehicle. The cost of the battery charger, the transformer expansion cost, and the cost of setting the electric outlet for the charger are considered to be part of the direct cost of the EV's. For the economic analysis, a perfect capital market and economic stability is assumed. Then, the direct cost of EV's is determined by following the next steps:

1. The direct cost due to the purchase price of EV's introduced in a given year is determined by multiplying the total number of new EV's of each type (NETYP) by their prices (PRCEV) which vary depending on the type of vehicle. Then, the costs of each type of vehicle are added in order to determine the direct cost due to the EV's purchase prices (DCFP). Equation (3.21) represents this procedure mathematically.

$$DCFP_i = \sum_{J=1}^{TYPE} [NETYP_{j,i}] * [PRCEV_j] \tag{3.21}$$

where:

DCFP= Direct cost of EV's introduced in year i due to EV's purchase prices.
TYPE= Number of types of vehicles.
NETYP= Number of EV's of type j introduced in year i.
PRCEV= Price of EV's of type j.

2. In order to determine the direct cost caused by the cost of the battery charger, the outlet, and the expansion of the service transformer, it is important to note that the owners of deteriorated EV's who are buying new EV's are exempt from setup costs. As a result, the equation to determine EV's setup costs (3.22) only includes the number of vehicles

introduced as a result of growth and forced retirement (if applicable) according to the type of scenario.

$$DCBT_i = [EVGR_i] * [BCOT] \tag{3.22}$$

where:

DCBT= Direct cost of EV's incurred by setup expenses.
EVGR= Number of EV's introduced in year i as a result of growth only.
BCOT= Battery charger, outlet and transformer expansion cost.

3. The total direct cost of EV's introduced in a given year is determined by adding the EV's direct costs due to EV's purchase prices (DCFP) and the costs caused by setup expenses (DCBT) in that year, as indicated in equation (3.23).

$$DCEV_i = DCFP_i + DCBT_i \tag{3.23}$$

where:

DCEV= Direct cost of EV's introduced in year i.
DCFP= Direct cost of EV's introduced in year i due to EV's purchase prices.
DCBT= Direct cost of EV's incurred by setup expenses.

4. The cumulative EV's direct cost (TDCV) is determined by adding the total EV's direct costs (DCEV) that have been incurred in previous years, from the time the pollution control program started to the current year (TIME). This cumulative direct cost is calculated with equation (3.24).

$$TDCV_i = \sum_{i=1}^{TIME} DCEV_i \tag{3.24}$$

where:

TDCV = Cumulative EV's direct cost in year i.
TIME = Current year.
DCEV = Direct cost of EV's introduced in year i.

### 3.3.3 EV's Energy Demand

The energy required to operate all the EV's in the system per year is determined in this section. The electricity demanded by EV's in a given year is determined with equation (3.25). This equation determines the energy demanded by the total number of EV's of each type (TETYP) considering the average distance traveled by these vehicles, their efficiencies, and the efficiency of the battery charger. The total energy demanded by all EV's in the system includes the energy demanded by the total number of vehicles of each type.

$$TEDS_i = \sum_{J=1}^{TYPE} [TETYP_{j,i}] * [EVADT_j] * [EVEFF_j] / [EFBC] \tag{3.25}$$

where:

TEDS =Total energy demanded by all EV's in the system in year i (KWh).
TYPE= Number of types of vehicles.
TETYP= Total number of EV's of type j in the system in year i.
EVADT= EV's average distance traveled per year (km).
EVEFF= Efficiency of EV's of type j (KWh/km).
EFBC = Efficiency of the battery recharger.

### 3.3.4 EV's Operational Cost

The operational cost of EV's is based on the cost of the energy consumed by these vehicles and the cost of battery replacement. Minor maintenance costs such as the cost of replacing tires, brake pads and shock absorbers are not considered. The battery cost is annualized so that this cost can be treated on a yearly basis. The operational costs will vary depending on the type of vehicle. Equation (3.26) is used to determine the operational costs of EV's in the system. The first term of this equation determines the cost of the energy demanded by the total number of EV's in the system in a given year. This cost is obtained by multiplying the total energy demanded (TEDS) by the electricity price (PREL). The second term of equation (3.26) determines the battery related costs for each type of vehicle in a given year. The battery prices are annualized and multiplied by the total number of EV's of each type.

$$OPCY_i = [TEDS_i * PREL] + \sum_{j=1}^{TYPE} [TETYP_{j,i} * BTPR_j \div BLFY_j] \tag{3.26}$$

where:

OPCY= EV's operational costs in year i.
TEDS= Total energy demanded by all EV's in the system in year i (KWh).
PREL= Electricity price (KWh/$).
TETYP= Total number of EV's of type j in the system in year i.
BTPR= Battery price of EV's of type j ($).
BLFY= Battery life of EV's of type j.

The EV's cumulative operational cost (OPCT) is determined by adding the total EV's operational costs (OPCY) that have been incurred in previous years, from the time the pollution control program started to the current year (TIME). This cumulative cost is calculated with equation (3.27).

$$OPCT_i = \sum_{i=1}^{TIME} OPCY_i \tag{3.27}$$

where:

OPCT= EV's cumulative operational cost.
OPCY= EV's operational cost in year i.

### 3.3.5 EV's Overall Cost

The EV's cumulative overall cost in a given year is determined by adding the EV's cumulative direct cost (TDCV) and the cumulative operational costs (OPCT) as determined for that year. The cumulative overall cost includes all the EV's costs that have been incurred from the beginning of the program to the current year and is determined with equation (3.28).

$$OCEV_i = TDCV_i + OPCT_i \tag{3.28}$$

where:

OVCT = EV's cumulative overall cost in year i.
TDCV = EV's cumulative direct cost in year i.
OPCT = EV's cumulative operational cost in year i.

### 3.3.6 Conventional Vehicle Costs

In order to determine the marginal cost of introducing EV's, it is necessary to determine the conventional vehicle related costs that would have to be paid if the EV's were not introduced. These costs refer to direct, maintenance, and operational costs of conventional vehicles . The following is the general equation to determine the ICV's cumulative costs:

$$ICVC_i = ICDC_i + ICOM_i \tag{3.29}$$

where:

ICVC = ICV's cumulative costs in year i.
ICDC = ICV's cumulative direct cost in year i.
ICOM = ICV's cumulative maintenance and operational costs in year i.

The direct cost of ICV's that would be introduced in place of EV's in a given year is determined by multiplying the total number of new EV's of each type (NETYP) by the ICV's price (PRICV) which varies depending on the type of vehicle. Then, the costs of each type of vehicle are added in order to determine the direct cost due to ICV's purchase prices (ICDY), as indicated in equation (3.30).

$$ICDY_i = \sum_{J=1}^{TYPE} [NETYP_{j,i}] * [PRICV_j] \tag{3.30}$$

where:

ICDY= Direct cost of ICV's introduced in year i.
NETYP= Number of EV's of type j introduced in year i.
PRICV= Price of ICV's of type j.

The ICV's cumulative direct cost (ICDC) is determined by adding the total ICV's direct costs (ICDY) that have been incurred in previous years, from the time the pollution control program started to the current year (TIME). This cumulative direct cost is calculated with equation (3.31).

$$ICDC_i = \sum_{i=1}^{TIME} ICDY_i \tag{3.31}$$

where:

ICDC= ICV's cumulative direct cost in year i.
ICDY= Direct cost of ICV's introduced in year i.

The ICV's operational costs include expenses related to maintenance and operation. The ICV's maintenance costs do not include the costs that were not considered to calculate the EV's maintenance costs, namely, cost of replacing tires, brake pads and shock absorbers. The total ICV's operational cost in a given year (ICOY) is determined with equation (3.32). The first term of this equation determines the cost due to the ICV's consumption of gasoline. In order to determine this cost, the total number of vehicles of each type, the average distance traveled by each type of vehicle, the efficiency of each type of vehicle and the price of gasoline are considered. The second term of equation (3.32), AMCY, refers to the average operational and maintenance costs of each type of vehicle.

$$ICOY_i = \sum_{j=1}^{TYPE} [TETYP_{j,i} * EVADT_j * GASP \div ICEFF_j] + [AMCY_j] \tag{3.32}$$

where:

ICOY= ICV's operational cost in year i.
TYPE= Number of types of vehicles.
TETYP= Total number of EV's of type j in the system in year i.
EVADT= Average distance traveled by vehicles of type j per year (km).
GASP= Gasoline price ($/lt.)
ICEFF= Efficiency of ICV's of type j (km/lt.).
AMCY= Average maintenance cost of ICV's of type j.

The ICV's cumulative operational cost (ICOM) is determined by adding the total ICV's operational costs (ICOY) that have been incurred in previous years, from the time the pollution control program started to the current year (TIME). This cumulative cost is calculated with equation (3.33).

$$ICOM_i = \sum_{i=1}^{TIME} ICOY_i \tag{3.33}$$

where:

ICOM= ICV's cumulative operational cost in year i.
ICOY= ICV's operational cost in year i.

### 3.3.7 Marginal Cost Incurred by EV's

The marginal cost of replacing conventional vehicles with electric vehicles in a given year is determined by subtracting the EV's cumulative costs from the ICV's cumulative costs as indicated in equation (3.34). These costs include the direct and operational costs of both, EV's and ICV's.

$$MCEV_i = [OVCT_i] - [ICVC_i] \tag{3.34}$$

where:

MCEV = EV's cumulative marginal cost in year i.
OVCT = EV's cumulative overall costs in year i.
ICVC = ICV's cumulative costs in year i.

It is important to note that the cost of damages caused by ICV's are not considered in this equation. These costs refer to the cost of damages to humans, vegetation, building materials, and aesthetic materials caused by the ICV's emissions. These costs are taken into consideration when EV's benefits are estimated.

### 3.3.8 Total Vehicle Miles Traveled

In order to determine the total emissions caused by the remaining ICV's in the system, the total number of vehicle miles traveled per year is required. This number of miles refers to the miles traveled by the ICV's that remain in the system in a given year. Equation (3.35) is used to determine this number of miles. In this equation, the total number of ICV's of each type (TITYP) remaining in the system in a given year is multiplied by the average distance traveled by each type of vehicle.

$$TVMT_i = \sum_{J=1}^{TYPE} TITYP_{j,i} * EVADT_j \div 1.6 \tag{3.35}$$

where:

TVMT= Total vehicle miles traveled in year i (mi)
TITYP= Total number of ICV's of type j in the system in year i.
EVADT= Average distance traveled by vehicles of type j per year (km).

*Note: the factor 1.6 is used to convert the distances given in kilometers to miles.

### 3.3.9 Emission Factors and ICV's Emissions

The emission factors used to calculate the reduction of emissions caused by the introduction of EV's in a given year is determined by using a program called MOBILE5. This program is used by the U.S. EPA and the government of Mexico to determine emissions of CO. $NO_x$, and HC from mobile sources. The program is written in FORTRAN 77 and can be used in a IBM-PC platform. This program requires an input file (INPUT.IN) that contains the values of specific parameters from the region of study such as altitude, temperatures, type of vehicles, vehicle miles traveled, type of gasoline, type of inspection and maintenance programs, and vehicles age distribution.

All the information required by MOBILE5 to determine emissions in MCMA is available. The value of parameters required by MOBILE5 are obtained from reports of the government of Mexico (DDF 1994) and from the "USERS GUIDE to MOBILE" (EPA 1994). However, changes in the input file of MOBILE5 have to be carried out in order to simulate the effects of EV's pollution control programs. There are critical parameters whose values change every year as a result of the introduction of EV's. These parameters are the age distributions of the ICV's remaining in the system. Consequently, the model developed in this study creates an input file for MOBILE5 with their respective values for each year. The input files are developed based on the FORTRAN format suggested by the "USERS GUIDE to MOBILE5" (EPA 1994).

In order to determine the emissions of ICV's remaining in the system the following steps are taken. First, the MOBILE input files are manually transferred to the MOBILE5 program. Second, the emission factors which are given in grams per mile are placed in a spreadsheet which contains the values of total vehicle miles traveled of each year. Third, within the spreadsheet the emissions factors and the total vehicle miles traveled are multiplied to determine the total emissions of CO, $NO_x$, and HC for each year.

For more information about the procedures that MOBILE5 uses to determine emission factors and MOBILE5 input alternatives, the following literature is suggested: "USERS GUIDE to MOBILE5" (EPA 1994), and "Evaluation of MOBILE Vehicle Emission Model" (US DOT 1994).

### 3.3.10 Reduction of Emissions and Air Quality

The reduction of emissions caused by the introduction of EV's is determined based on the emissions generated by the remaining ICV's in the system and the emissions that the ICV's will generate if no action is taken. In other words, the results obtained from the scenarios

LIRS, MIRS, HIRS, and FRTS, which include alternatives to reduce emissions, are compared to the values obtained from the no action taken scenario (NATS). The reduction of emissions is the substraction of emissions caused by the remaining ICV's in a given scenario from the emissions of ICV's in the no action taken scenario.

In order to find out the percentage of reduction of total emissions in the system, the inventory of emissions of MCMA is used. Table 3.1 presents the percentage of emissions per sector. With the information provided in Table 3.1 and the percentage of reduction of emissions caused by the replacement of ICV's (private vehicles), it is possible to determine the total reduction of emissions in percentages. For instance, if it is determined that the reduction emissions of CO caused by private vehicles is 5% in a given year, the total reduction of emissions of CO in the system will be 2.65% (0.05 x 53.11%). It is important to note that this criterion is applicable only if no changes occur in the other sectors. That is, the emission contribution of all sectors, excluding the private vehicles sector, will be the same over the years. This assumption is made because the future contributions of emissions from other sectors are unknown. After determining the reduction of total emissions, the effects of reducing emissions on air quality are estimated. In order to determine the changes on air pollutant concentrations caused by the reduction of emissions, the information provided by two studies is used. These two studies which were carried out by the Los Alamos National Laboratory and the Instituto Mexicano del Petroleo (the research institute of the Mexican oil company) are the "Mexico City Air Quality Research Initiative, Volume III, Modeling and Simulation" (LANL 1994) and the

Table 3.1 Private Vehicles Contribution to Total Emissions.
(DDF 1996, pg. 75).

| Sector | CO | $NO_x$ | HC |
|---|---|---|---|
| Industry | 0.37% | 24.50% | 3.23% |
| Services | 0.00% | 0.00% | 36.94% |
| Private Vehicles* | **53.11%** | **30.71%** | **30.06%** |
| Taxis | 22.46% | 12.42% | 12.34% |
| Other Vehicles | 24.03% | 28.22% | 11.74% |
| Nature | 0.00% | 0.00% | 3.79% |
| Others | 0.04% | 4.15% | 1.90% |
| Total | 100% | 100% | 100% |

* Cars, light duty pick-ups, and vans.

"Mexico City Air Quality Research Initiative, Volume V, Strategic Evaluation" (LANL 1994a). These two studies provide the functional relationship between emissions and air pollution concentrations. Also, they determined the effects on air quality of 58 air pollution control programs based on the annual reduction of emissions and the percentage of total reduction of emissions. The concentration units used in these two studies were IMECAS which are normalized values based on the permissible level of each pollutant. The maximum permissible limit of any type of pollutant is 100 IMECAS.

In this study, the emission-concentration relations for each pollutant is determined based on a regression analysis. The results from the 58 air pollution control programs considered in the two studies previously mentioned are used to carry out this analysis. The emission-concentration relations found were the following:

$$RCO = 0.005 + (0.77) * (\%\ of\ total\ reduction\ of\ emissions\ of\ CO) \tag{3.36}$$

$$RNO = 0.003 + (0.74) * (\%\ of\ total\ reduction\ of\ emissions\ of\ NOx) \tag{3.37}$$

$$\begin{aligned} ROZ = (2.263) * (NOx\ reduction,\ \%\ of\ total) + \\ (0.3) * (HC\ reduction,\ \%\ of\ total) \end{aligned} \tag{3.38}$$

where:

RCO= Reduction of CO (IMECAS)
RNO= Reduction of NOx (IMECAS)
ROZ= Reduction of ozone (IMECAS)

The R squared for the three equations is higher than 0.999 and their standard errors are lower than 0.04. For more information about the regression analysis and the procedure to determine the IMECAS see Appendix A.

### 3.3.11 EV's Benefits

In this section, the equations and criteria used to estimate the benefits of reducing air pollution in Mexico City and its Metropolitan Area are presented. The benefits include health benefits, reduction in damages to material, improved visibility, increase crop production, enhanced property values and others. It is important to note that "the benefits... may take different forms, occur at different times, involve different degrees of uncertainty, and affect different individuals." (Halvorsen and Ruby 1981). Another point considered is that in Mexico City and its Metropolitan Area, most of the air pollution damages are caused by ozone. (LANL 1994a and DDF 1996).

**Health Benefits (HLTB).** The Department of Health of Mexico carried out several studies to determine the effects of air pollutants on human health in Mexico City and its Metropolitan Area (MCMA). Their objective was to calculate the percentage of population affected at different levels of concentration of ozone; the concentration levels were given in IMECAS. They analyzed different health problems such as severe headaches, conjunctivitis, severe cough, dyspnea, odinofagia, dysphonia, and eye irritation.

In order to determine health benefits caused by the implementation of EV's programs, this study considers the population that suffers from severe headaches. It is assumed that severe headaches are correlated with other type of health problems, work absenteeism, work accidents, low efficiency, and street accidents caused by air pollution.

The results obtained by the Health Department of Mexico indicates that the relationship between the percentage of population affected by severe headaches per IMECA (of ozone) is 0.069% of the total population, within the range of 100 to 300 IMECAS (DDF 1996).

The U.S. General Accounting Office (GAO 1994) reported that in the U.S. in 1990, the willingness to pay to avoid one day of different symptoms caused by air pollution was estimated by the Industrial Economics , Inc. (IEc) which was hired by the EPA to analyze benefits of air pollution control programs. The symptoms that were considered were the following: throat congestion, coughing, asthma attack, eye irritation, headache, shortness of breath, nausea, drowsiness, allergy (chronic), angina pectoris, bronchitis and emphysema (chronic). The IEc's study reported that people were willing to pay the following amount of money to avoid one day of headaches: Low: $1.26, Best:$25.16, and High: $50.44 (1990 dollars). For this study, the dollar amount considered is $6.51 based on the following assumption: the Gross National Product (GPN) per person per day , $6.51, is considered as the value of negative effects of air pollution per person per day. This amount of money is to cover medical expenses, accident costs, distress, and discomfort per person per day.

In order to formulate the equation to determine health benefits, it is important to point out that if no action is taken to reduce emissions in MCMA, there will be more than 333 days above permissible levels and the average level of maximum values of IMECAS during a year will be above 200 points (DDF 1996). To determine the health benefits it is necessary to determine the number of people who will avoid suffering from severe headaches as a result of the implementation of pollution control programs. This number of people is determine by using the dose-response relation for severe headaches, found by the Health Department of Mexico, which indicates that the population affected per IMECA of ozone is 0.069% of the total population. The dose-response (0.00069) is multiplied by the number of IMECAS reduced and by the total population in the metropolitan area in a given year. The resulting number is the number of people who will avoid suffering from severe headaches (PPSV). This relation is represented mathematically with equation (3.39).

$$PPSV_i = (0.069\%) * (IMRD_i) * (TPOP_i) \div (100) \tag{3.39}$$

where:

PPSV= Population saved from severed headaches in year i.
IMRD= Number of IMECAS reduced in year i.
TPOP= Total population in year i. (Annual population growth rate 2%).

The health benefits (HLTB) are determined by multiplying the number of days in which the permissible levels are violated by the cost of damage avoided per person per day and the total number of people who will avoid suffering. That is, the health benefits are equal to the damages avoided ($6.51 per person-day) due to the reduction of concentration of ozone during the 333 days in which ozone levels are approximately two times above permissible limits. This relation is represented with equation (3.40).

$$HLTB_i = (333 days/year) * (\$6.51\ per\ person\text{-}day) * (PPSV_i) \tag{3.40}$$

where:

HLTB= Health benefits in year i ($/year).
PPSV= Population saved from severed headaches in year i.

**Material Benefits (MTLB).** The U. S. National Commission on Air Quality (NCAQ 1981) reported that the value of damage avoided by meeting air quality standards for selected metals, fabrics, building materials, rubber and plastic to be $ 3.95 billion (1978 dollars). If this amount of money is updated to 1996 dollars, considering a conservative inflation rate of 2%. this value becomes $5.64 billion or $23.5 per capita. The NCAQ also reported that sulfur dioxide and ozone, whose corrosive effects on materials can not be separated, create the largest savings of cost avoided, 97% of total costs.

Halvorsen and Ruby (1981) reported that the presence of pollution in the air increases the rate of corrosion of certain metals such as steel, reducing their service life exponentially. Other types of relationships between service life of specific metals and different doses (concentrations) of air pollutants were reported. Although the damages of metals can be reduced by protecting them from corrosion by providing a protective coating of plastic or paint which incurs extra costs, there is still deterioration of these protective materials. It was found that oil-based exterior paints are subject to significant film erosion from sulfur dioxide and ozone. Halvorsen and Ruby reported linear effects of sulfur dioxide on the erosion rate of paint. They reported that the "data available do not permit the construction of a dose-response function for ozone, although the effect appears to be of approximately the same severity."

In addition, effects of ozone on others type of materials such as fabrics and rubber were reported. Nitrogen dioxide and ozone accelerate the fading of dyes in various fabrics. Numerous studies have evaluated the fading of specific fabrics and dyes when exposed to air pollutants. However, most of the fading studies have been oriented more toward identifying the sensitive pollutant-dye-fabric combinations than toward measuring fading rates for ozone and nitrogen dioxide concentrations. For the effects of ozone on rubber, it was found that ozone causes rubber and similar elastomers to become brittle and crack. "Several studies of the service life of rubber products at varying ozone levels have been reported, but the relations they suggest are not consistent." (Halvorsen and Ruby 1981). Since in Mexico City the levels of ozone are approximately two times the permissibie limit (194.29 IMECAS on the average) 333 days out of the year, any reduction of ozone levels will contribute to the benefit of materials.

Assumptions:

1. The cost of materials namely, metals, building materials, rubber and plastics, in the U.S. are the same as the cost of materials in Mexico (many of these materials are imported from the U.S.).

2. The material benefits of reducing the level of ozone from the current average level (194.29 IMECAS) to the permissible level (100 IMECAS) is $11.75 per capita per year. This amount, $11.75, is half the material benefits of reducing air pollution to permissible levels in the U.S., $23.5 per capita. Since ozone and sulfur dioxide, which is not considered in this study, are the two air pollutants that affect materials approximately with the same severity (Halvorsen and Ruby 1981), it was considered that ozone was responsible for only one half of the benefits, $11.75 per capita per year. In addition, a linear relationship between the reduction of IMECAS and the benefits is considered. In other words, 94.29 IMECAS is equal to 100% of pollution and $11.75/person per year is the

maximum benefit an individual can obtain if the IMECA is reduced to 100 points. That is. per every IMECA reduced the benefit is \$0.12/person.

Based on the previous assumptions, the number of IMECAS reduced (IMRD) is multiplied by the material benefit per person (\$0.12) and the total population in the metropolitan area in order to determine the material benefits in a given year. This relation is represented with the following equation:

$$MTLB_i=(IMRD_i)*(\$0.12/person)*(TPOP_i) \qquad (3.41)$$

where:

MLTB= Material benefits in year i.
IMRD= Number of IMECAS reduced in year i.
TPOP= Total population in year i. (Annual population growth rate 2%).

**Visibility, Crop Production, and Property Value Benefits (VCPB).** A number of studies (Halvorsen et al. 1981, Ahmad 1981, NCAQ 1981) have found that the main determined "quantifiable" benefits of reducing air pollution are the improvement of health conditions and the reduction in damage of materials. For instance, when the different type of benefits reported by the NCAQ, namely, health benefits, improved crop production, reduction in damages to materials, enhanced property values and improved visibility are compared, health and material benefits account for 86% of total benefits. Another study (Halvorsen et al. 1981) analyzed human health, vegetation, materials and soiling benefits. Halvorsen reported that human and material benefits account for 83.6% of total benefits caused by the air-pollution control in the United States in 1979.

Based on the reports of the NCAQ and Halvorsen, this study assumes that if only health, material, visibility, crop production and property value benefits are considered, health and material benefits will account for 85% of total benefits and the benefits of improved visibility, increased crop production, and enhanced property values (VCPB) will account for 15% of total benefits. In other words, the VCPB equals is 15/85 (or 0.1765) the sum of health benefits plus material benefits. This relation is represented as follows:

$$VCPB_i = (HLTB_i + MTLB_i) * (0.1765) \tag{3.42}$$

where:

VCPB= Visibility, crop production, and property value benefits in year i.
HLTB= Health benefits in year i.
MLTB= Material benefits in year i.

**Other Benefits (OTHB).** There are other two categories of benefits that have not been considered, the non quantifiable benefits and the undetermined quantifiable benefits. The non-quantifible benefits refer to the avoidance to the non-valuable damages such as birth defects, increase of mortality rate, degradation of comfort, deterioration of recreational values, deterioration of historical buildings, and destruction of aesthetic materials among others. The undetermined quantifible benefits refer to specific human health problems (chronic bronchitis, impairment of psychomotor functions, and cancer), damages to animals, devaluation to public and private gardens and others. Since the determination of all these damages are beyond the scope of this study. Thus, for this study, other benefits (OTHB) are set equal to zero.

**Total Benefits**. The total benefits include health benefits, reduction in damages to material, improved visibility, improved crop production, enhanced property values and other benefits. In order to estimate the total benefits, the following equation is used:

$$TotalBenefits = HLTB_i + MTLB_i + VCPB_i + OTHB_i \qquad (3.43)$$

where:

HLTB= Health benefits in year i.
MTLB= Material benefits in year i.
VCPB= Visibility, crop production, and property value benefits in year i.
OTHB= Other Benefits in year i (equal to zero).

### 3.3.12 Model Translation

The procedure and formulas described from section 3.3.1 to section 3.3.9 have been translated into a computer program written in FORTRAN. The program is called EVCAP (Electric Vehicle Costs and Air Pollution). The source code (evcap.for) and the executable file (evcap.exe) are located on a 3.5" floppy disk attached to this document or available upon request to the author. The input required by this program are a number of files which are described in Section 3.4. These input files (filename.in) are also located in the floppy disk attached to this document. The input files are written in text form (ASCII) and can be readily modified. Thus, if the values of parameters such as the prices of vehicles, electricity price. vehicle efficiencies, battery life, and others change, the files can be opened. modified, and saved in TXT form with almost any word processor for PC-IBM platforms.

When EVCAP is executed, it automatically reads the information from the input files after the users indicate the type of scenario that will be simulated. EVCAP asks the users what type of scenario will be simulated, if initial conditions will be printed, if

MOBILE input files will be created, if a file with all results will be created (to be read into a spread sheet), and if results will be printed on paper.

The output files that EVCAP creates for MOBILE5 are named as follows: S# - YEAR.IN, where # is the scenario number and YEAR is the year number (in this study, the values of YEAR are from 1 to 20). For instance, if the low introduction rate scenario (LIRS) is number one, the output files for this scenario will be S1-01.IN, S1-02.IN, ... S1-20.in. The other type of files that EVCAP generates are the files that contain the general results from the simulation. These results are the following: time (year), total number of vehicles in the system (TNVS), total number of ICV's in the system (TNIC), total number of EV's in the system (TNEV), EV's marginal cost (MCEV), and total vehicle miles traveled (TVMT). EVCAP generates only one file of general results per scenario. This file is called S# - OUT.TXT, where # is the scenario number, and is formatted so that it can be read by a spread sheet-based program such as Quatro Pro or Excel.

With the emission factors obtained from MOBILE5 and the general results of EVCAP, the total emissions of remaining ICV's in the system, the reduction of emissions, and the benefits are determined following the procedures described in Section 3.3.9, 3.3.10, and 3.3.11 respectively. In order to automate these procedures, the equations developed in these three sections are incorporated into a spread sheet of general results (GRSLTS.W2B) which is an expansion of the EVCAP output file of general results.

### 3.4 Input Data

After the pertinent elements (variables and parameters) of the system were defined. the next steps were to collect and analyze the data needed by the simulation model. Actual information from Mexico City and its Metropolitan Area and from EV's studies was used to select or determine the value of parameters. EVCAP gives the option to print the values of the parameters (input data) of each scenario by printing initial conditions. Also, the values of these parameters can be changed at any time due to the flexibility of EVCAP. The input data used in this study is presented as follows:

1. Total number of private vehicles in the system= 2,200,000 (adjusted to year 2000) (DDF 1996, pg. 84)

2. Vehicle growth rate= 1% (low rate) (DDF 1994, pg. II-7).

3. EV's market share (for low introduction rate scenario, LIRS):

2%. 2%. 2%. 5%, 10%, 10%, 15%, 15%, 20%, 25%,

30%, 35%, 40%, 45%, 50%, 55%, 60%, 65%, 70%, 75%

3. ICV's age distribution (DDF 1996, pg 85):

8.74%, 8.48%, 8.12%, 7.66%, 7.56%, 7.02%, 6.48%, 5.94%, 5.11%

4.42%, 3.91%, 3.57%, 3.35%, 3.12%, 2.88%, 2.64%, 2.10%, 1.82%

1.61%, 1.47%. 1.12%, 1.00%, 0.84%, 0.64%, 0.40%

* Note: deterioration rates were determined from ICV's age distributions.

4. Number of ICV's of each age: this number was determined based on the total number of vehicles in the system and their respective age distribution.

5. Types of vehicles= 3. (Two-passenger EV's, four-passenger Ev's and EV mini-vans)

6. Battery charger, outlet, and transformer expansion costs= $800.00 (Luz y Fuerza, Mexican utility company, 1996: direct contact) and (Sotelo. 1996)

7. Battery charger efficiency= 80% (based on the 1994 proceedings of the Electric Vehicle Association of the Americas (EVVA) and other EV's reports).

8. Electricity price= $0.04/KWh (Mexican utility company, 1996).

9. Gasoline price= $0.31/liter (Mexican oil company, 1996).

The rest of the information is presented in Table 3.2. In general, this information was obtained from or determined based on reports of the Mexican Government, automobile manufacturers, Mexican private associations, and electric vehicle proceedings. In order for EVCAP to be able to read the value of the parameters, the data is written in different input files which have a predefined name

and format. The name of these files and their FORTRAN format is described in Table 3.3.

### 3.5 Verification and Validation

In order to determine the correctness of the model, it was verified and validated. The verification process consisted of isolating and correcting unintentional errors in the model by using the software built in debugging tools. The verification process included a walk-through procedure which involved going through the model subroutine by subroutine and manually in order to analyze specific logic or elements interactions.

Table 3.2 Vehicle Characteristics, Input Data.

| Vehicles | Two-Passenger | Four-Passenger | Mini-van |
|---|---|---|---|
| % of each type | 49.7% | 37.6% | 12.7% |
| ICV's price ($) | 8,000 | 15,000 | 20,000 |
| ICV M&O costs ($/year) | 350 | 400 | 500 |
| ICV' efficiency (Km/l) | 11 | 10 | 9 |
| EV's price ($) | 15,000 | 20,000 | 30,000 |
| EV's efficiency (KWh/km) | 0.20 | 0.20 | 0.30 |
| Battery price ($) | 2500 | 3000 | 3100 |
| Battery life (km) | 128,000 | 140,000 | 160,000 |
| Average distance travel/year (km) | 20,000 | 20,000 | 25,000 |

Table 3.3 Input Files and Their FORTRAN Format.

| Description | File Name | FORTRAN Format |
|---|---|---|
| Vehicle growth rate | FVGRT.IN | F5.2 |
| EV market share | FEVMK.IN | 3(12F5.2) |
| ICV deterioration rates | FICDR.IN | 3(10F8.5) |
| EV deterioration rates | FEVDR.IN | 3(10F8.5) |
| Number of vehicles | FTNVS.IN | F9.1 |
| ICV age distributions | FAGI.IN | 5(5F7.4) |
| Types of vehicles | FTYPE.IN | I2 |
| Percentage of each type | FPVTYP.IN | 6F6.3 |
| EV prices | FPRCEV.IN | 6F8.1 |
| EV setup costs | FBCOT.IN | F7.1 |
| EV distance traveled | EVADT.IN | 6F8.1 |
| EV efficiencies | FEVEFF.IN | 6F8.2 |
| Electricity price | FPREL.IN | F7.2 |
| EV battery prices | FBTLF.IN | 6F9.1 |
| Battery prices | FBTLF.IN | 6F9.1 |
| Battery lives | FBTLF.IN | 6F9.1 |
| Charger efficiency | FEFBC.IN | F6.3 |
| ICV prices | FPRICV.IN | 6F8.1 |
| ICV efficiencies | FICEFF.IN | 6F6.2 |
| ICV maintenance costs | FAMCY.IN | 6F8.2 |
| Gasoline price | FGASP.IN | F6.2 |

In this study, the model represents a system that does not yet exist. That is, electric vehicles are not being substituted for gasoline-powered vehicles in Mexico City and its Metropolitan Area yet. Thus, validation can not proceed by direct experimentation. However, different tests were used to judge the validity of the model. These tests focused on the reasonableness of model behavior such as continuity, consistency, degeneracy and absurd conditions. "One can argue philosophically as to whether it is even possible to talk about validating a model of a proposed system; yet we obviously must convince ourselves and others that the observed model behavior is actually giving us indications of how the proposed referent system would behave if implemented." (Pegden et al. 1990).

Continuity was tested by making small changes in the input parameters and analyzing the effects of this change on the output. In general, small changes in the input parameters caused small, but appropriate, changes in the output and in other variables within the system. For instance, EV's prices, battery prices, and EV's deterioration rates were modified for different scenarios. As a result there were reasonable variations in the output.

In order to test consistency, similar runs were carried out and the results were compared among runs. Essentially, similar runs of the model yield similar results. Degeneracy was tested by removing certain features of the model and analyzing the effects of this change in the model behavior. Overall, when certain features of the model were removed, the output reflected their removal. For instance, the EV's operational cost, the energy demand, and the vehicle dynamic subroutines were deactivated. As a result, in the first case, the overall cost of EV's was reduced. In the other two cases, error messages were found. Absurd conditions such as an extremely large number of vehicles entering the system and extremely high prices of batteries were introduced. These changes were also proportionally reflected on the output.

Also, based on information from 1990, the model was tested when the EV's introduction rate is equal to zero (that is, when there are only ICV's in the system). The ICV's emissions determined with MOBILE5 were similar to the emissions reported for MCMA in 1990. Namely, in this study, the values of emissions (thousands of tones) of HC, CO, and $NO_x$ were 173.08, 1150.99, and 41.50, respectively, and 141.00, 1328.10, and 41.90 in a study carried out by the government of Mexico (UNEP/WHO 1994). The relatively small differences between the emissions determined with MOBILE5 and the emissions determine by Mexican officials in 1990, in part, are due to the different software packages and procedures used by the Mexican government in 1990. In this year, the software package available to determine emission factors was MOBILE3 which was released in 1989. MOBILE5a which is used in this study was improved and released in March 1993.

The previously mentioned tests were part of both the verification and validation processes. Another procedure used to analyze the validity of the model was a sensitivity analysis which is described in the next section.

### 3.6 Experimentation and Results

Five different scenarios were simulated. These scenarios were the low introduction rate scenario (LIRS), moderate introduction rate scenario (MIRS), high introduction rate scenario (HIRS), no action taken scenario (NATS), and forced retirement scenario (FRTS).

All these scenarios are described in Section 3.1. The period of study for all scenarios is 20 years. It is assumed that the programs to control air pollution with EV's will be implemented at the beginning of the year 2000. Consequently, the information obtained covers a period from year 2000 to 2020. (The results of each scenario are presented and compared in Chapter 4).

Also, as part of the experimentation and validation of this study, a sensitivity analysis was carried out. The values of input parameters were modified and the effects of these changes on the behavior of the model were analyzed. The parameters studied and their impact on the model are described as follows:

1. EV's market share. The percentage of EV's introduced per year in the low introduction rate was modified. Five cases were analyzed, namely, Base-case (based on the ZEV law from California), 2%- Increase case, 4%-Increase case, 0%-case and 100%-case. The values of the EV's market share were the following:

Base-case (or Cal-case) :

2%, 2%, 2%, 5%, 5%, 10%, 10%, 15%, 15%, 20%, 25%,

30%, 35%, 40%, 45%, 50%, 55%, 60%, 65%, 70%, 75%

2%-Increase case:

2%, 4%. 6%, 8%, 10%, 12%, 14%, 16%, 18%, 20%, 22%

24%, 26%, 28%, 30%, 32%, 34%, 36%, 38%, 40%, 42%

4%-Increase case:

4%, 8%, 12%, 16%, 20%, 24%, 28%, 32%, 36%, 40%, 44%,

48%, 52%, 56%, 60%, 64%, 68%, 72%, 76%, 80%, 84%

For the 0%-case, the value of the EV's market share was zero; that is, no EV's were introduced in this case. For the 100%-case, the value of the EV's market share was 100%; that is, all the vehicles introduced were EV's.

The effects of the different market share values on a number of variables were compared. The variables analyzed were the total number of ICV's in the system (TNIC), total number of EV's in the system (TNEV), total marginal costs (MCST), total vehicle miles traveled by the remaining ICV's in the system (TVMT), reduction of emissions of HC (REHC), reduction of emissions of CO (REOC), and reduction of emissions of $NO_x$ (RENO) from year 2000 to year 2020. The reduction of emissions in percentages, REHC, REOC, and RENO, were determined based on the no action taken scenario (NATS). That is, the emissions of the no action taken scenario are equal to 100% of total emissions caused by private ICV's. The changes in the values of all these variables were proportional to the variation of the market share values. The results obtained for TNIC, TNEV, MCST, TVMT, REHC, REOC, and RENO are represented graphically in figure 3.2, 3.3, 3.4, 3.5, 3.6, 3.7, and 3.8, respectively.

2. <u>EV's deterioration rates</u>. The percentages of vehicles lost per year was modified in the moderate introduction rate scenario. For the base case (Evdr-base), it was assumed that EV's and ICV's had the same deterioration rate. Since it is expected that EV's will be more reliable than ICV's, the percentage of vehicles lost per year will be lower as a result of deterioration. These analysis considered four cases, namely, the base case (Evdr-base) and other three cases (Evdr-10%, Evdr-20%, and Evdr-30%) where the vehicles lost per year are 10%, 20%, and 30% less than the vehicles lost in the base case, respectively. For

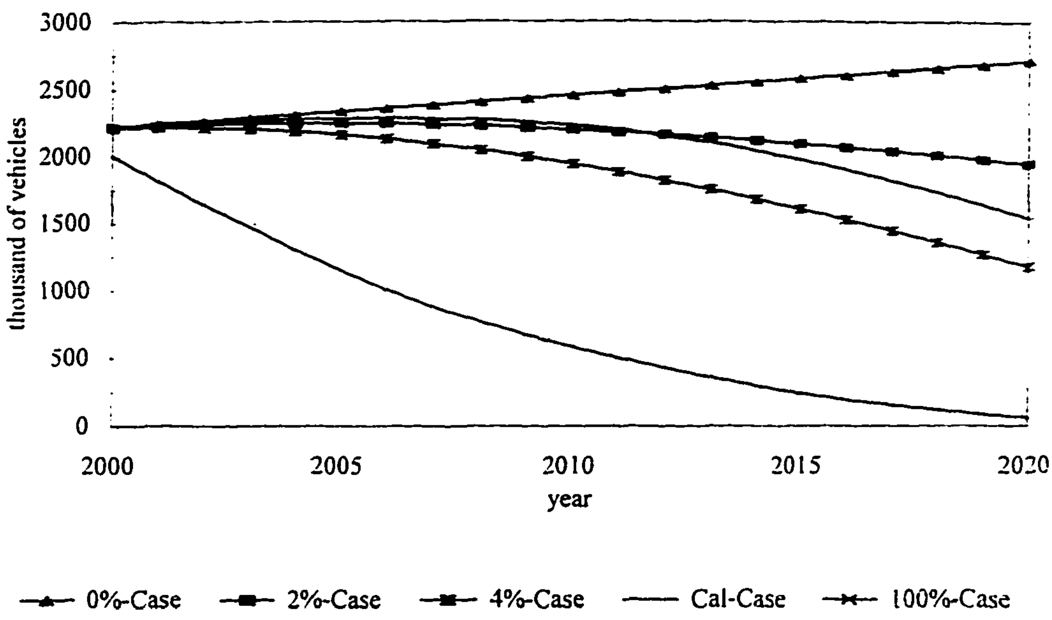


Figure 3.2 Effects of Introduction Rates on Total Number of ICV's.

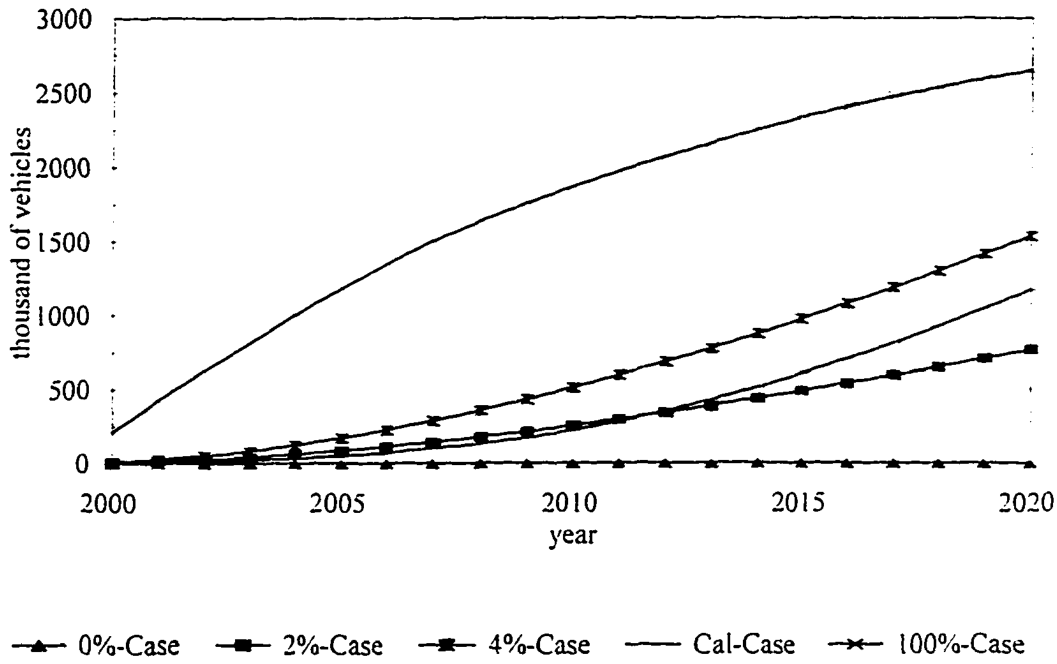


Figure 3.3 Effects of Introduction Rates on Total Number of EV's.

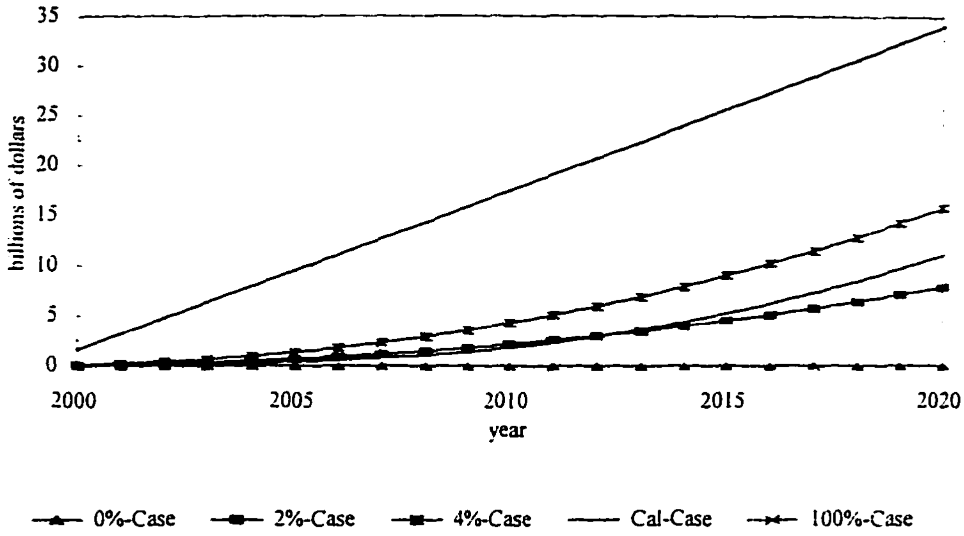


Figure 3.4 Effects of Introduction Rates on Marginal Costs.

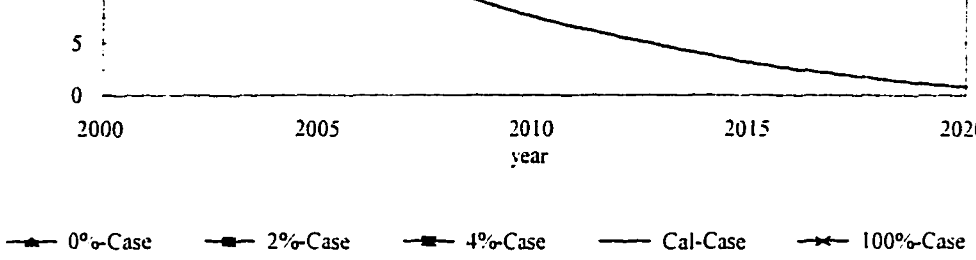


Figure 3.5 Effects of Introduction Rates on Total ICV's Miles Traveled.

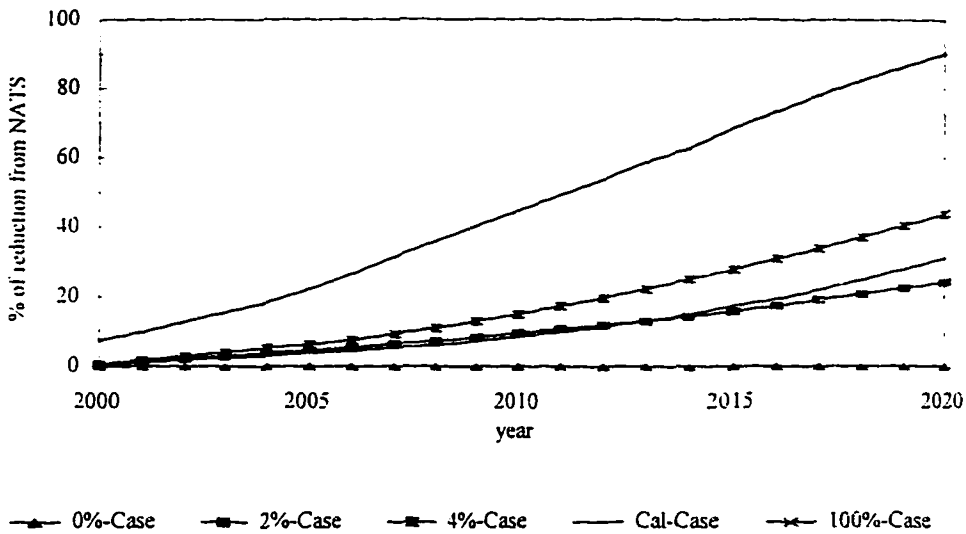


Figure 3.6 Effects of EV's Introduction Rates on Reduction of HC.

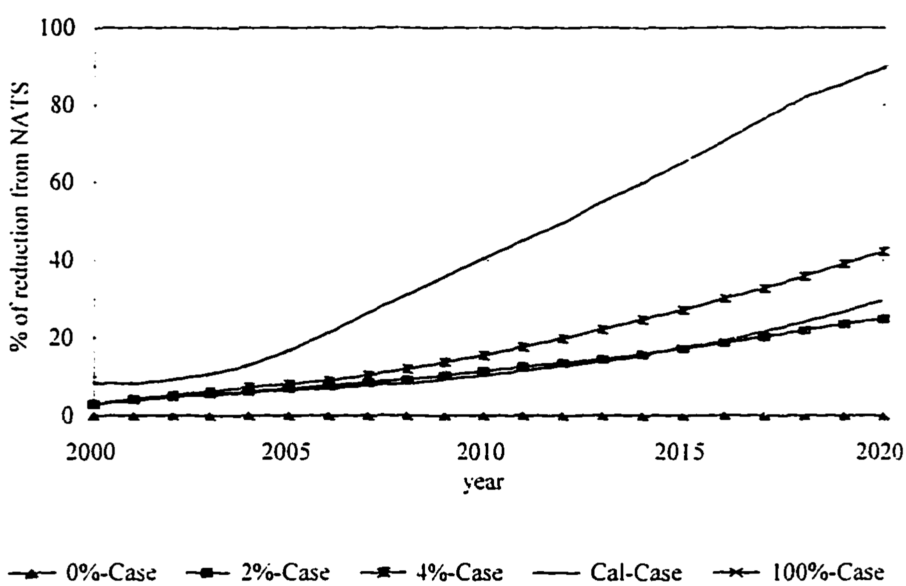


Figure 3.7 Effects of EV's Introduction Rates on Reduction of CO.

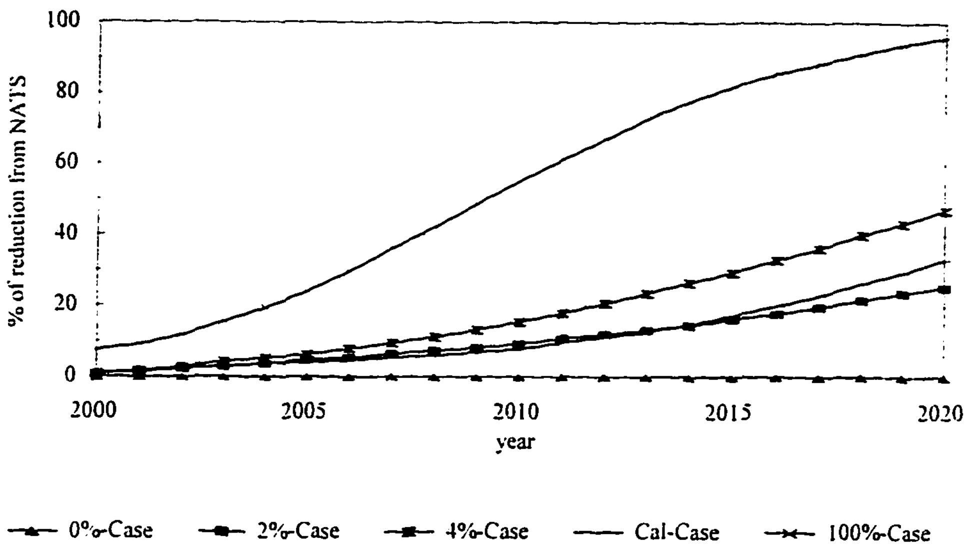


Figure 3.8 Effects of EV's Introduction Rates on Reduction of $NO_x$.

example, if 3% of the total number vehicles in the system are lost in a given year in the Evdr-base case, the vehicles lost in the Evdr-10%, Evdr-20%, and Evdr-30% cases are 2.7%, 2.4%, and 2.1% of the total vehicles in the system, respectively. In this example, the deterioration rates for the Evdr-base, Evdr-10%, Evdr-20%, and Evdr-30% are 0.970, 0.973, 0.976, and 0.979, respectively.

Table 3.3 and Figure 3.9 show that the EV's marginal cost decreases when the vehicle deterioration rates improve. This results show that the behavior of the marginal cost variable (MCST) is consistent with and proportional to the variation of deterioration rates.

3. EV's prices. Four cases with different EV's prices were analyzed. The prices of 2-passenger EV's (2P-EV), 4-passenger EV's (4P-EV), and EV mini-vans EV-MV) were the following: Base-case: $15,000, $20,000, and $30,000; Case 1: $12,800, $18,300, and $24,400; Case 2: $10,400, 16,650, and 23,200; Case 3: $8,000, $15,000, and $20,000, respectively. The EV's prices for Case 3 (or ICprc-case) are the same prices of ICV's. Figure 3.10 shows the effects of EV's prices on the marginal costs for the moderate introduction rate scenario (MIRS). It is observed that the marginal costs are significantly sensitive to the EV's prices. Small reduction of EV's prices causes significant reductions in the marginal costs. In Case 3, where the EV's prices are equal to the ICV's prices, the marginal costs were expected to be equal or less than zero since the EV's operational costs are slightly lower than the ICV's operational costs, as shown in Table 3.4. However, the marginal costs were greater than zero due to the battery charger, outlet, and transformer

Table 3.3 Effects of EV's Deterioration Rates on Marginal Costs.

| Year | EVs Marginal Costs | | | |
|---|---|---|---|---|
| | Evdr-base | Evdr-10% | Evdr-20% | Evdr-30% |
| 2000 | 1.590 | 1.590 | 1.590 | 1.590 |
| 2001 | 3.180 | 3.176 | 3.172 | 3.167 |
| 2002 | 4.770 | 4.756 | 4.741 | 4.727 |
| 2003 | 6.360 | 6.328 | 6.297 | 6.265 |
| 2004 | 7.951 | 7.900 | 7.849 | 7.798 |
| 2005 | 9.543 | 9.464 | 9.385 | 9.306 |
| 2006 | 11.136 | 11.021 | 10.906 | 10.790 |
| 2007 | 12.732 | 12.573 | 12.414 | 12.253 |
| 2008 | 14.330 | 14.117 | 13.902 | 13.685 |
| 2009 | 15.932 | 15.656 | 15.377 | 15.094 |
| 2010 | 17.539 | 17.195 | 16.845 | 16.489 |
| 2011 | 19.153 | 18.735 | 18.310 | 17.875 |
| 2012 | 20.774 | 20.278 | 19.772 | 19.255 |
| 2013 | 22.402 | 21.824 | 21.234 | 20.629 |
| 2014 | 24.040 | 23.375 | 22.695 | 21.998 |
| 2015 | 25.686 | 24.930 | 24.156 | 23.362 |
| 2016 | 27.343 | 26.492 | 25.620 | 24.725 |
| 2017 | 29.010 | 28.062 | 27.088 | 26.088 |
| 2018 | 30.689 | 29.640 | 28.563 | 27.453 |
| 2019 | 32.381 | 31.228 | 30.042 | 28.821 |
| 2020 | 34.084 | 32.828 | 31.534 | 30.200 |

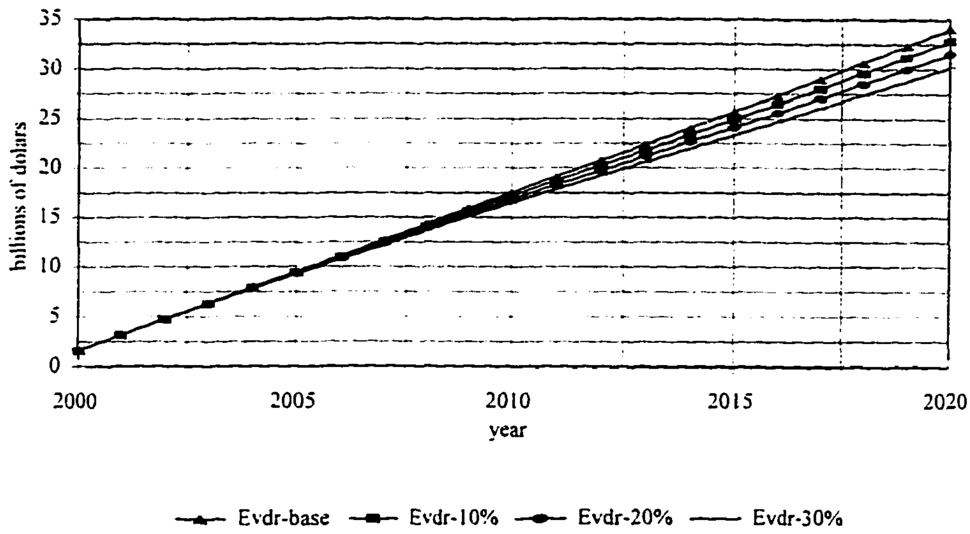


Figure 3.9 Effects of EV's Deterioration Rates on Marginal Costs.

Table 3.4 Cumulative Operational Costs for the Moderate Rate Scenario.

| Year | Operational Costs EV's | Operational Costs ICV's | Operational Costs Marginal |
|---|---|---|---|
| | (billions of dollars) | | |
| 2000 | 0.132 | 0.133 | -0.002 |
| 2001 | 0.392 | 0.397 | -0.005 |
| 2002 | 0.775 | 0.785 | -0.010 |
| 2003 | 1.277 | 1.293 | -0.016 |
| 2004 | 1.894 | 1.918 | -0.024 |
| 2005 | 2.621 | 2.654 | -0.033 |
| 2006 | 3.450 | 3.494 | -0.044 |
| 2007 | 4.373 | 4.429 | -0.056 |
| 2008 | 5.381 | 5.449 | -0.069 |
| 2009 | 6.462 | 6.545 | -0.083 |
| 2010 | 7.612 | 7.709 | -0.097 |
| 2011 | 8.825 | 8.938 | -0.113 |
| 2012 | 10.099 | 10.228 | -0.129 |
| 2013 | 11.430 | 11.576 | -0.146 |
| 2014 | 12.816 | 12.979 | -0.164 |
| 2015 | 14.253 | 14.435 | -0.182 |
| 2016 | 15.734 | 15.935 | -0.201 |
| 2017 | 17.256 | 17.476 | -0.220 |
| 2018 | 18.816 | 19.056 | -0.240 |
| 2019 | 20.412 | 20.673 | -0.261 |
| 2020 | 22.040 | 22.321 | -0.281 |

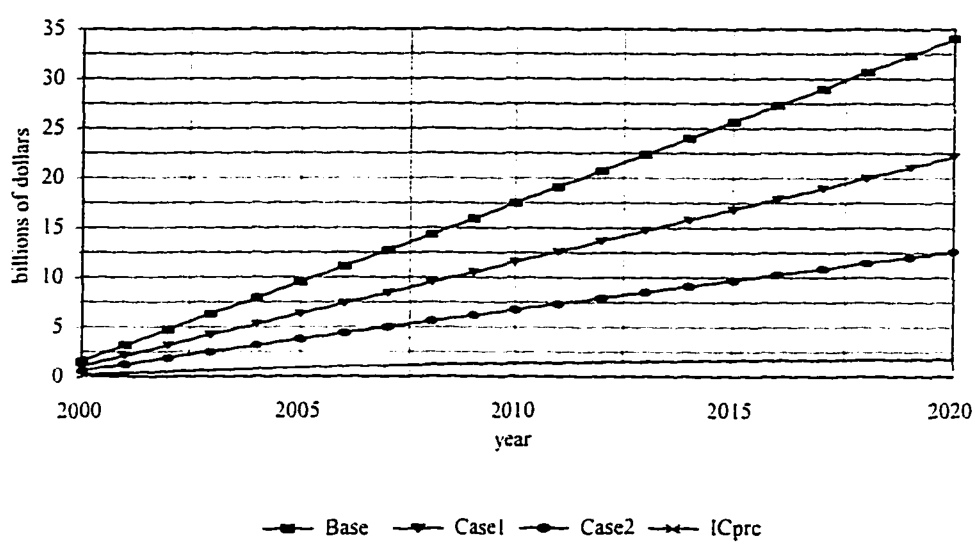


Figure 3.10 EV's Prices Effect on Marginal Costs.

expansion costs which are part of the EV's direct costs. That is, the direct cost of EV's includes the EV's price plus setup costs.

4. Battery prices. The prices of the EV's batteries were changed in the moderate introduction rate scenario. The prices for the 2P-EV, 4P-EV, and EV-MV batteries were the following: Base-case: $2,500, $3,000, and $3,100; LESS15-case: $2,125, $2,550, and $2,635; LESS30-case: $1,750, $2,100, and $2,170; LESS45-case: $1,375, $1,650, and $1,705; respectively. The battery prices in the LESS15, LESS30, and LESS45 cases are 15%, 30%, and 45% lower than the battery prices in the Base-case, respectively. Figure 3.11 shows the effects of the different battery prices on the marginal costs. It is observed that the variations of marginal costs are consistent with the changes of the battery prices. The lower the battery prices are the lower the marginal costs are. The reduction of marginal costs due to the reduction of battery prices is significant also. Nevertheless, the EV's prices are the majority of the total cost of introducing EV's into the system, as shown in Figure 3.10.

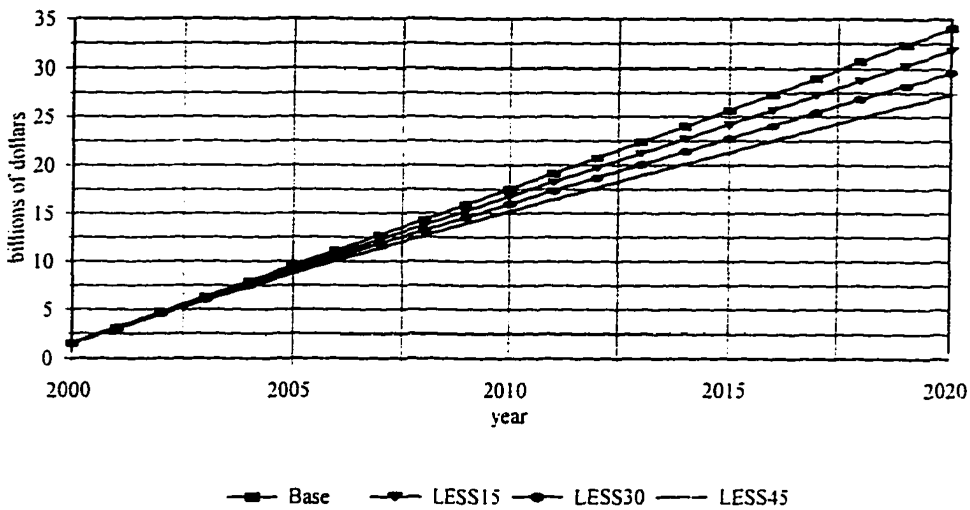


Figure 3.11 Effects of Battery Prices on Marginal Costs.

# CHAPTER 4

# ANALYSIS OF RESULTS

This chapter presents and analyzes the results of four programs to reduce air pollution in Mexico City and its Metropolitan Area (MCMA). Three of these programs consider the introduction of electric vehicles (EV's) and/or the replacement of the oldest conventional vehicles with EV's. The other program considers the replacement of the oldest conventional vehicles with new ICV's. These four programs are represented by the low introduction rate scenario (LIRS), moderate introduction rate scenario (MIRS), high introduction rate scenario (HIRS), and forced retirement scenario (FRTS), respectively. The characteristics of these scenarios are given in section 3.1. Also, the results of the no action taken scenario (NATS) are presented and are used as a reference point to compare the results of all scenarios.

The general results of each of these scenarios are presented in Table 4.1, 4.2, 4.3, 4.4 and 4.5. The first column (1) of these tables shows the years considered in this study, from year 2000 to year 2020. The following three columns (2, 3, and 4) include the total number of vehicles in the system (TNVS), the total number of ICV's that remain in the system (TNIC), and the total number of EV's in the system (TNEV) for each year, respectively. The next two columns (5 and 6) include the yearly marginal cost (MCVY) and the cumulative marginal cost (MCEV) of implementing a pollution control program for each year in billions of 1996 dollars. The following column (7) presents the total miles

Table 4.1 General Results for the Low Introduction Rate Scenario (LIRS).

| YEAR | TNVS | TNIC (Vehicles) | TNEV | MCVY | MCEV (billions of 1996 dollars) | TVMT (miles) | HC | CO (g/mi) | NOx | HC | CO (ICV emissions; thousands of tons) | NOx |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 2000 | 2,222,000 | 2,217,715 | 4,286 | 0.032 | 0.032 | 2.860E+10 | 5.26 | 32.07 | 1.66 | 150.44 | 917.25 | 47.48 |
| 2001 | 2,244,220 | 2,235,759 | 8,461 | 0.032 | 0.064 | 2.883E+10 | 5.23 | 31.82 | 1.65 | 150.80 | 917.51 | 47.58 |
| 2002 | 2,266,662 | 2,254,180 | 12,483 | 0.032 | 0.095 | 2.907E+10 | 5.20 | 31.56 | 1.64 | 151.17 | 917.51 | 47.68 |
| 2003 | 2,289,329 | 2,266,490 | 22,839 | 0.080 | 0.176 | 2.923E+10 | 5.19 | 31.52 | 1.64 | 151.71 | 921.35 | 47.94 |
| 2004 | 2,312,222 | 2,279,242 | 32,980 | 0.080 | 0.256 | 2.940E+10 | 5.18 | 31.42 | 1.63 | 152.27 | 923.59 | 47.91 |
| 2005 | 2,335,344 | 2,281,668 | 53,677 | 0.162 | 0.418 | 2.943E+10 | 5.18 | 31.49 | 1.64 | 152.43 | 926.64 | 48.26 |
| 2006 | 2,358,698 | 2,285,087 | 73,611 | 0.162 | 0.580 | 2.947E+10 | 5.20 | 31.67 | 1.64 | 153.25 | 933.33 | 48.33 |
| 2007 | 2,382,285 | 2,278,165 | 104,120 | 0.246 | 0.827 | 2.938E+10 | 5.21 | 31.77 | 1.65 | 153.08 | 933.44 | 48.48 |
| 2008 | 2,406,108 | 2,272,809 | 133,298 | 0.248 | 1.074 | 2.931E+10 | 5.24 | 32.05 | 1.66 | 153.60 | 939.45 | 48.66 |
| 2009 | 2,430,169 | 2,257,222 | 172,947 | 0.334 | 1.408 | 2.911E+10 | 5.26 | 32.20 | 1.67 | 153.12 | 937.38 | 48.62 |
| 2010 | 2,454,470 | 2,232,174 | 222,296 | 0.421 | 1.829 | 2.879E+10 | 5.30 | 32.52 | 1.69 | 152.58 | 936.19 | 48.65 |
| 2011 | 2,479,015 | 2,197,697 | 281,319 | 0.509 | 2.339 | 2.834E+10 | 5.35 | 32.91 | 1.70 | 151.64 | 932.78 | 48.18 |
| 2012 | 2,503,805 | 2,154,708 | 349,097 | 0.597 | 2.935 | 2.779E+10 | 5.42 | 33.43 | 1.72 | 150.62 | 928.99 | 47.80 |
| 2013 | 2,528,843 | 2,103,392 | 425,451 | 0.686 | 3.621 | 2.713E+10 | 5.51 | 34.15 | 1.75 | 149.47 | 926.39 | 47.47 |
| 2014 | 2,554,132 | 2,043,960 | 510,172 | 0.777 | 4.398 | 2.636E+10 | 5.60 | 34.87 | 1.78 | 147.62 | 919.20 | 46.92 |
| 2015 | 2,579,673 | 1,976,981 | 602,692 | 0.868 | 5.266 | 2.550E+10 | 5.68 | 35.49 | 1.80 | 144.82 | 904.88 | 45.89 |
| 2016 | 2,605,470 | 1,902,316 | 703,154 | 0.965 | 6.231 | 2.453E+10 | 5.83 | 36.57 | 1.83 | 143.03 | 897.21 | 44.90 |
| 2017 | 2,631,525 | 1,820,667 | 810,858 | 1.060 | 7.291 | 2.348E+10 | 5.94 | 37.39 | 1.86 | 139.48 | 877.95 | 43.67 |
| 2018 | 2,657,840 | 1,732,627 | 925,213 | 1.157 | 8.448 | 2.235E+10 | 6.07 | 38.42 | 1.89 | 135.64 | 858.51 | 42.23 |
| 2019 | 2,684,418 | 1,638,882 | 1,045,536 | 1.253 | 9.701 | 2.114E+10 | 6.22 | 39.55 | 1.93 | 131.47 | 835.95 | 40.79 |
| 2020 | 2,711,263 | 1,539,314 | 1,171,949 | 1.354 | 11.055 | 1.985E+10 | 6.39 | 40.83 | 1.97 | 126.86 | 810.57 | 39.11 |

TNVS= Total number of vehicles in the system.
TNIC= Total number of ICV's in the system.
TNEV= Total number of EV's in the system.
MCVY= EV's marginal costs per year.
MCEV= EV's cumulative marginal costs.
TVMT= Total vehicle miles traveled.

Table 4.2 General Results for the Moderate Introduction Rate Scenario (MIRS).

| YEAR | TNVS | TNIC | TNEV | MCVY | MCEV | TVMT | HC | CO | NOx | HC | CO | NOx |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | (vehicles) | | (billions of 1996 dollars) | | (miles) | | (g/mi) | | (ICV emissions; thousands of tons) | | |
| 2000 | 2,222,000 | 2,007,722 | 214,278 | 1.590 | 1.590 | 2.589E+10 | 5.40 | 33.41 | 1.71 | 139.82 | 865.10 | 44.28 |
| 2001 | 2,244,220 | 1,821,165 | 423,056 | 1.590 | 3.180 | 2.349E+10 | 5.85 | 37.30 | 1.87 | 137.40 | 876.08 | 43.92 |
| 2002 | 2,266,662 | 1,642,527 | 624,136 | 1.590 | 4.770 | 2.118E+10 | 6.34 | 41.34 | 2.03 | 134.30 | 875.72 | 43.00 |
| 2003 | 2,289,329 | 1,474,008 | 815,321 | 1.590 | 6.360 | 1.901E+10 | 6.92 | 45.74 | 2.19 | 131.55 | 869.52 | 41.63 |
| 2004 | 2,312,222 | 1,307,688 | 1,004,534 | 1.591 | 7.951 | 1.687E+10 | 7.61 | 50.74 | 2.38 | 128.34 | 855.73 | 40.14 |
| 2005 | 2,335,344 | 1,153,249 | 1,182,095 | 1.592 | 9.543 | 1.487E+10 | 8.30 | 55.58 | 2.57 | 123.45 | 826.66 | 38.22 |
| 2006 | 2,358,698 | 1,010,689 | 1,348,009 | 1.593 | 11.136 | 1.303E+10 | 9.02 | 60.52 | 2.74 | 117.57 | 788.86 | 35.72 |
| 2007 | 2,382,285 | 880,009 | 1,502,276 | 1.595 | 12.732 | 1.135E+10 | 9.77 | 65.64 | 2.89 | 110.88 | 744.97 | 32.80 |
| 2008 | 2,406,108 | 767,588 | 1,638,519 | 1.598 | 14.330 | 9.899E+09 | 10.56 | 71.18 | 3.02 | 104.54 | 704.65 | 29.90 |
| 2009 | 2,430,169 | 670,348 | 1,759,821 | 1.602 | 15.932 | 8.645E+09 | 11.37 | 76.86 | 3.10 | 98.30 | 664.48 | 26.80 |
| 2010 | 2,454,470 | 584,327 | 1,870,143 | 1.607 | 17.539 | 7.536E+09 | 12.19 | 82.58 | 3.15 | 91.86 | 622.32 | 23.74 |
| 2011 | 2,479,015 | 505,787 | 1,973,228 | 1.614 | 19.153 | 6.523E+09 | 13.05 | 88.93 | 3.17 | 85.13 | 580.10 | 20.68 |
| 2012 | 2,503,805 | 432,086 | 2,071,719 | 1.621 | 20.774 | 5.573E+09 | 14.08 | 96.54 | 3.19 | 78.46 | 537.97 | 17.78 |
| 2013 | 2,528,843 | 363,446 | 2,165,398 | 1.629 | 22.402 | 4.687E+09 | 15.09 | 103.35 | 3.14 | 70.73 | 484.43 | 14.72 |
| 2014 | 2,554,132 | 300,085 | 2,254,047 | 1.637 | 24.040 | 3.870E+09 | 16.67 | 112.63 | 3.15 | 64.52 | 435.90 | 12.19 |
| 2015 | 2,579,673 | 242,004 | 2,337,669 | 1.647 | 25.686 | 3.121E+09 | 17.63 | 121.87 | 3.18 | 55.02 | 380.37 | 9.93 |
| 2016 | 2,605,470 | 195,803 | 2,409,667 | 1.656 | 27.343 | 2.525E+09 | 18.67 | 128.30 | 3.17 | 47.15 | 323.99 | 8.01 |
| 2017 | 2,631,525 | 155,763 | 2,475,762 | 1.668 | 29.010 | 2.009E+09 | 19.42 | 129.76 | 3.20 | 39.01 | 260.67 | 6.43 |
| 2018 | 2,657,840 | 120,342 | 2,537,498 | 1.679 | 30.689 | 1.552E+09 | 20.26 | 130.23 | 3.19 | 31.44 | 202.12 | 4.95 |
| 2019 | 2,684,418 | 88,001 | 2,596,417 | 1.691 | 32.381 | 1.135E+09 | 21.66 | 143.29 | 3.01 | 24.58 | 162.63 | 3.42 |
| 2020 | 2,711,263 | 63,361 | 2,647,902 | 1.703 | 34.084 | 8.172E+08 | 21.69 | 144.14 | 2.94 | 17.72 | 117.79 | 2.40 |

TNVS= Total number of vehicles in the system. TNEV= Total number of EV's in the system. MCEV= EV's cumulative marginal costs.
TNIC= Total number of ICV's in the system. MCVY= EV's marginal costs per year. TVMT= Total vehicle miles traveled.

Table 4.3 General Results for the High Introduction Rate Scenario (HIRS).

| YEAR | TNVS | TNIC (vehicles) | TNEV | MCVY (billions of 1996 dollars) | MCEV | TVMT (miles) | HC | CO (g/mi) | NOx | HC (ICV emissions; thousands of tons) | CO | NOx |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 2000 | 2,222,000 | 1,998,922 | 223,078 | 1.655 | 1.655 | 2.578E+10 | 5.38 | 33.26 | 1.71 | 138.70 | 857.44 | 44.08 |
| 2001 | 2,244,220 | 1,798,285 | 445,935 | 1.696 | 3.352 | 2.319E+10 | 5.76 | 36.75 | 1.86 | 133.59 | 852.32 | 43.14 |
| 2002 | 2,266,662 | 1,601,167 | 665,496 | 1.732 | 5.084 | 2.065E+10 | 6.17 | 40.18 | 2.02 | 127.41 | 829.72 | 41.71 |
| 2003 | 2,289,329 | 1,410,648 | 878,680 | 1.764 | 6.847 | 1.819E+10 | 6.59 | 43.58 | 2.18 | 119.89 | 792.85 | 39.66 |
| 2004 | 2,312,222 | 1,219,689 | 1,092,533 | 1.789 | 8.636 | 1.573E+10 | 7.09 | 47.32 | 2.36 | 111.53 | 744.35 | 37.12 |
| 2005 | 2,335,344 | 1,032,909 | 1,302,435 | 1.854 | 10.491 | 1.332E+10 | 7.53 | 50.76 | 2.53 | 100.31 | 676.19 | 33.70 |
| 2006 | 2,358,698 | 854,929 | 1,503,769 | 1.889 | 12.380 | 1.103E+10 | 7.90 | 53.04 | 2.69 | 87.10 | 584.81 | 29.66 |
| 2007 | 2,382,285 | 684,208 | 1,698,077 | 1.938 | 14.317 | 8.824E+09 | 8.18 | 54.44 | 2.85 | 72.18 | 480.39 | 25.15 |
| 2008 | 2,406,108 | 525,587 | 1,880,520 | 2.003 | 16.321 | 6.778E+09 | 8.40 | 55.68 | 2.97 | 56.94 | 377.42 | 20.13 |
| 2009 | 2,430,169 | 370,266 | 2,059,903 | 2.114 | 18.435 | 4.775E+09 | 8.58 | 56.38 | 3.07 | 40.97 | 269.23 | 14.66 |
| 2010 | 2,454,470 | 284,245 | 2,170,226 | 1.712 | 20.147 | 3.666E+09 | 9.03 | 59.32 | 3.15 | 33.10 | 217.46 | 11.55 |
| 2011 | 2,479,015 | 205,704 | 2,273,312 | 1.732 | 21.879 | 2.653E+09 | 9.50 | 62.76 | 3.20 | 25.20 | 166.50 | 8.49 |
| 2012 | 2,503,805 | 132,002 | 2,371,803 | 1.748 | 23.627 | 1.702E+09 | 10.15 | 67.62 | 3.25 | 17.28 | 115.12 | 5.53 |
| 2013 | 2,528,843 | 63,361 | 2,465,482 | 1.760 | 25.386 | 8.172E+08 | 10.41 | 66.78 | 3.09 | 8.51 | 54.57 | 2.53 |
| 2014 | 2,554,132 | 0 | 2,554,132 | 1.791 | 27.177 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 2015 | 2,579,673 | 0 | 2,579,673 | 1.373 | 28.550 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 2016 | 2,605,470 | 0 | 2,605,470 | 1.466 | 30.016 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 2017 | 2,631,525 | 0 | 2,631,525 | 1.515 | 31.531 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 2018 | 2,657,840 | 0 | 2,657,840 | 1.534 | 33.066 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 2019 | 2,684,418 | 0 | 2,684,418 | 1.562 | 34.628 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 2020 | 2,711,263 | 0 | 2,711,263 | 1.608 | 36.237 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

TNVS= Total number of vehicles in the system.
TNIC= Total number of ICV's in the system.
TNEV= Total number of EV's in the system.
MCVY= EV's marginal costs per year.
MCEV= EV's cumulative marginal costs.
TVMT= Total vehicle miles traveled.

Table 4.4 General Results for the No Action Taken Scenario (NATS).

| YEAR | TNVS | TNIC | TNEV | MCEV | TVMT | HC | CO | NOx | HC | CO | NOx |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | (number of vehicles) | | | (dollars) | (miles) | | (g/mi) | | (ICV emissions; thousands of tonnes) | | |
| 2000 | 2,222,000 | 2,222,000 | 0 | 0 | 2.866E+10 | 5.27 | 33.00 | 1.67 | 151.02 | 945.68 | 47.86 |
| 2001 | 2,244,220 | 2,244,220 | 0 | 0 | 2.894E+10 | 5.27 | 33.00 | 1.67 | 152.53 | 955.13 | 48.34 |
| 2002 | 2,266,662 | 2,266,662 | 0 | 0 | 2.923E+10 | 5.27 | 33.00 | 1.67 | 154.06 | 964.68 | 48.82 |
| 2003 | 2,289,329 | 2,289,329 | 0 | 0 | 2.953E+10 | 5.27 | 33.00 | 1.67 | 155.60 | 974.33 | 49.31 |
| 2004 | 2,312,222 | 2,312,222 | 0 | 0 | 2.982E+10 | 5.27 | 33.00 | 1.67 | 157.15 | 984.07 | 49.80 |
| 2005 | 2,335,344 | 2,335,344 | 0 | 0 | 3.012E+10 | 5.27 | 33.00 | 1.67 | 158.73 | 993.92 | 50.30 |
| 2006 | 2,358,698 | 2,358,698 | 0 | 0 | 3.042E+10 | 5.27 | 33.00 | 1.67 | 160.31 | 1003.85 | 50.80 |
| 2007 | 2,382,285 | 2,382,285 | 0 | 0 | 3.072E+10 | 5.27 | 33.00 | 1.67 | 161.92 | 1013.89 | 51.31 |
| 2008 | 2,406,108 | 2,406,108 | 0 | 0 | 3.103E+10 | 5.27 | 33.00 | 1.67 | 163.53 | 1024.03 | 51.82 |
| 2009 | 2,430,169 | 2,430,169 | 0 | 0 | 3.134E+10 | 5.27 | 33.00 | 1.67 | 165.17 | 1034.27 | 52.34 |
| 2010 | 2,454,470 | 2,454,470 | 0 | 0 | 3.165E+10 | 5.27 | 33.00 | 1.67 | 166.82 | 1044.61 | 52.86 |
| 2011 | 2,479,015 | 2,479,015 | 0 | 0 | 3.197E+10 | 5.27 | 33.00 | 1.67 | 168.49 | 1055.06 | 53.39 |
| 2012 | 2,503,805 | 2,503,805 | 0 | 0 | 3.229E+10 | 5.27 | 33.00 | 1.67 | 170.17 | 1065.61 | 53.93 |
| 2013 | 2,528,843 | 2,528,843 | 0 | 0 | 3.261E+10 | 5.27 | 33.00 | 1.67 | 171.88 | 1076.27 | 54.47 |
| 2014 | 2,554,132 | 2,554,132 | 0 | 0 | 3.294E+10 | 5.27 | 33.00 | 1.67 | 173.60 | 1087.03 | 55.01 |
| 2015 | 2,579,673 | 2,579,673 | 0 | 0 | 3.327E+10 | 5.27 | 33.00 | 1.67 | 175.33 | 1097.90 | 55.56 |
| 2016 | 2,605,470 | 2,605,470 | 0 | 0 | 3.360E+10 | 5.27 | 33.00 | 1.67 | 177.08 | 1108.88 | 56.12 |
| 2017 | 2,631,525 | 2,631,525 | 0 | 0 | 3.394E+10 | 5.27 | 33.00 | 1.67 | 178.86 | 1119.97 | 56.68 |
| 2018 | 2,657,840 | 2,657,840 | 0 | 0 | 3.428E+10 | 5.27 | 33.00 | 1.67 | 180.64 | 1131.17 | 57.24 |
| 2019 | 2,684,418 | 2,684,418 | 0 | 0 | 3.462E+10 | 5.27 | 33.00 | 1.67 | 182.45 | 1142.48 | 57.82 |
| 2020 | 2,711,263 | 2,711,263 | 0 | 0 | 3.497E+10 | 5.27 | 33.00 | 1.67 | 184.28 | 1153.90 | 58.39 |

TNVS= Total number of vehicles in the system. TNEV= Total number of EV's in the system. TVMT= Total vehicle miles traveled.
TNIC= Total number of ICV's in the system. MCEV= EV's cumulative marginal costs.

Table 4.5 General Results for the Forced Retirement Scenario (FRTS).

| YEAR | TNVS | TNIC | TNEV | MCST | TVMT | HC | CO | NOx | HC | CO | NOx |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | (vehicles) | | (billion $) | (miles) | | (g/mi) | | | (ICV emissions, thousands of tons) | |
| 2000 | 2222000 | 2222000 | 0 | 0.107 | 2.866E+10 | 5.23 | 31.87 | 1.66 | 149.88 | 913.29 | 47.57 |
| 2001 | 2244220 | 2244220 | 0 | 0.385 | 2.894E+10 | 5.13 | 31.08 | 1.63 | 148.48 | 899.56 | 47.18 |
| 2002 | 2266662 | 2266662 | 0 | 0.781 | 2.923E+10 | 5.03 | 30.26 | 1.61 | 147.04 | 884.59 | 47.06 |
| 2003 | 2289329 | 2289329 | 0 | 1.273 | 2.953E+10 | 4.88 | 29.19 | 1.59 | 144.08 | 861.84 | 46.95 |
| 2004 | 2312222 | 2312222 | 0 | 1.840 | 2.982E+10 | 4.75 | 28.29 | 1.57 | 141.65 | 843.62 | 46.82 |
| 2005 | 2335344 | 2335344 | 0 | 2.533 | 3.012E+10 | 4.63 | 27.57 | 1.54 | 139.45 | 830.37 | 46.38 |
| 2006 | 2358698 | 2358698 | 0 | 3.356 | 3.042E+10 | 4.50 | 26.56 | 1.52 | 136.89 | 807.95 | 46.24 |
| 2007 | 2382285 | 2382285 | 0 | 4.274 | 3.072E+10 | 4.37 | 25.49 | 1.50 | 134.26 | 783.16 | 46.09 |
| 2008 | 2406108 | 2406108 | 0 | 5.322 | 3.103E+10 | 4.26 | 24.64 | 1.48 | 132.19 | 764.61 | 45.93 |
| 2009 | 2430169 | 2430169 | 0 | 6.590 | 3.134E+10 | 4.13 | 23.66 | 1.45 | 129.44 | 741.54 | 45.45 |
| 2010 | 2454470 | 2454470 | 0 | 7.296 | 3.165E+10 | 4.15 | 23.83 | 1.45 | 131.37 | 754.34 | 45.90 |
| 2011 | 2479015 | 2479015 | 0 | 8.002 | 3.197E+10 | 4.20 | 24.31 | 1.48 | 134.28 | 777.23 | 47.32 |
| 2012 | 2503805 | 2503805 | 0 | 8.708 | 3.229E+10 | 4.23 | 25.05 | 1.51 | 136.59 | 808.90 | 48.76 |
| 2013 | 2528843 | 2528843 | 0 | 9.414 | 3.261E+10 | 4.28 | 25.05 | 1.51 | 139.59 | 816.98 | 49.25 |
| 2014 | 2554132 | 2554132 | 0 | 10.120 | 3.294E+10 | 4.34 | 25.40 | 1.53 | 142.96 | 836.68 | 50.40 |
| 2015 | 2579673 | 2579673 | 0 | 10.939 | 3.327E+10 | 4.35 | 25.48 | 1.54 | 144.72 | 847.71 | 51.24 |
| 2016 | 2605470 | 2605470 | 0 | 11.782 | 3.360E+10 | 4.35 | 25.44 | 1.54 | 146.17 | 854.85 | 51.75 |
| 2017 | 2631525 | 2631525 | 0 | 12.647 | 3.394E+10 | 4.35 | 25.34 | 1.53 | 147.63 | 860.00 | 51.93 |
| 2018 | 2657840 | 2657840 | 0 | 13.533 | 3.428E+10 | 4.34 | 25.28 | 1.53 | 148.77 | 866.54 | 52.45 |
| 2019 | 2684418 | 2684418 | 0 | 14.434 | 3.462E+10 | 4.33 | 25.24 | 1.53 | 149.91 | 873.82 | 52.97 |
| 2020 | 2711263 | 2711263 | 0 | 15.374 | 3.497E+10 | 4.33 | 25.20 | 1.52 | 151.41 | 881.16 | 53.15 |

TNVS= Total number of vehicles in the system. TNEV= Total number of EV's in the system. TVMT= Total vehicle miles traveled.
TNIC= Total number of ICV's in the system. MCST= Cumulative marginal costs.

traveled by the ICV's that remain in the system each year (TVMT). The next three columns (8, 9, and 10) present the emission factors of HC, CO and $NO_x$ determined with MOBILE5 in grams per mile. The last three columns (11, 12, and 13) show the total emissions of HC, CO, and $NO_x$ generated by the ICV's that remain in the system in a given year. The results presented in these tables are explained and discussed in the following sections.

### 4.1 Comparison of Emissions from All Scenarios

In this section, the emissions in each scenario caused by the private ICV's after the implementation of air pollution control programs are compared to each other. The pollution control programs refer to the four scenarios previously discussed, namely, LIRS, MIRS, HIRS, and FRTS. The emissions from the no action taken scenario, NATS, are considered as the basis for comparison. The emissions of hydrocarbon (HC), carbon monoxide (CO), and nitrogen oxides ($NO_x$) from all scenarios are presented in Table 4.6, 4.7 and 4.8, respectively. Also, these emissions are represented graphically in Figure 4.1, 4.2, and 4.3, respectively. The pattern that the variation of emissions of one type of pollutant (HC, CO, or $NO_x$) follows is similar to the pattern of the other two pollutants. In all cases, the emissions in the scenarios that include pollution control programs are lower than the emissions in the no action taken scenario. The emissions in the low introduction rate scenario, LIRS, are slightly lower than the emissions in the no action taken scenario, NATS, during the first 10 years. After these ten years, the difference of emissions in the LIRS and the NATS becomes larger; the emissions in the NATS increase over the time while the emissions in the LIRS remain at approximately the same level from the beginning of the program, 2000,

Table 4.6 Emissions of Hydrocarbon from Private Vehicles.

| YEAR | HC (thousands of tons) | | | | |
|---|---|---|---|---|---|
| | LIRS | MIRS | HIRS | NATS | FRTS |
| 2000 | 150.44 | 139.82 | 138.70 | 151.02 | 149.88 |
| 2001 | 150.80 | 137.40 | 133.59 | 152.53 | 148.48 |
| 2002 | 151.17 | 134.30 | 127.41 | 154.06 | 147.04 |
| 2003 | 151.71 | 131.55 | 119.89 | 155.60 | 144.08 |
| 2004 | 152.27 | 128.34 | 111.53 | 157.15 | 141.65 |
| 2005 | 152.43 | 123.45 | 100.31 | 158.73 | 139.45 |
| 2006 | 153.25 | 117.57 | 87.10 | 160.31 | 136.89 |
| 2007 | 153.08 | 110.88 | 72.18 | 161.92 | 134.26 |
| 2008 | 153.60 | 104.54 | 56.94 | 163.53 | 132.19 |
| 2009 | 153.12 | 98.30 | 40.97 | 165.17 | 129.44 |
| 2010 | 152.58 | 91.86 | 33.10 | 166.82 | 131.37 |
| 2011 | 151.64 | 85.13 | 25.20 | 168.49 | 134.28 |
| 2012 | 150.62 | 78.46 | 17.28 | 170.17 | 136.59 |
| 2013 | 149.47 | 70.73 | 8.51 | 171.88 | 139.59 |
| 2014 | 147.62 | 64.52 | 0.00 | 173.60 | 142.96 |
| 2015 | 144.82 | 55.02 | 0.00 | 175.33 | 144.72 |
| 2016 | 143.03 | 47.15 | 0.00 | 177.08 | 146.17 |
| 2017 | 139.48 | 39.01 | 0.00 | 178.86 | 147.63 |
| 2018 | 135.64 | 31.44 | 0.00 | 180.64 | 148.77 |
| 2019 | 131.47 | 24.58 | 0.00 | 182.45 | 149.91 |
| 2020 | 126.86 | 17.72 | 0.00 | 184.28 | 151.41 |

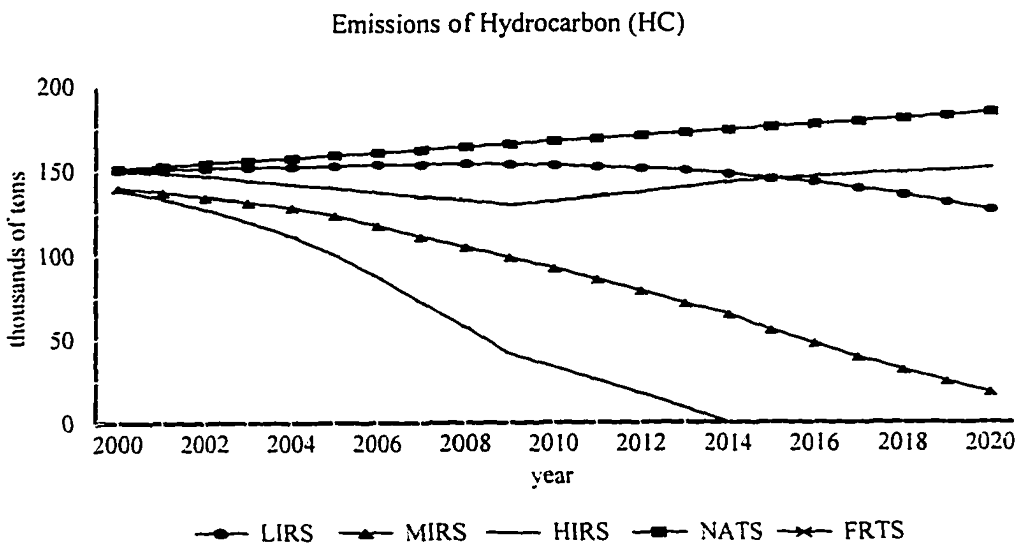


Figure 4.1 Emissions of Hydrocarbon from Private Vehicles.

Table 4.7 Emissions of Carbon Monoxide from Private Vehicles.

| YEAR | CO (thousands of tons) | | | | |
|---|---|---|---|---|---|
| | LIRS | MIRS | HIRS | NATS | FRTS |
| 2000 | 917.25 | 865.10 | 857.44 | 945.68 | 913.29 |
| 2001 | 917.51 | 876.08 | 852.32 | 955.13 | 899.56 |
| 2002 | 917.51 | 875.72 | 829.72 | 964.68 | 884.59 |
| 2003 | 921.35 | 869.52 | 792.85 | 974.33 | 861.84 |
| 2004 | 923.59 | 855.73 | 744.35 | 984.07 | 843.62 |
| 2005 | 926.64 | 826.66 | 676.19 | 993.92 | 830.37 |
| 2006 | 933.33 | 788.86 | 584.81 | 1003.85 | 807.95 |
| 2007 | 933.44 | 744.97 | 480.39 | 1013.89 | 783.16 |
| 2008 | 939.45 | 704.65 | 377.42 | 1024.03 | 764.61 |
| 2009 | 937.38 | 664.48 | 269.23 | 1034.27 | 741.54 |
| 2010 | 936.19 | 622.32 | 217.46 | 1044.61 | 754.34 |
| 2011 | 932.78 | 580.10 | 166.50 | 1055.06 | 777.23 |
| 2012 | 928.99 | 537.97 | 115.12 | 1065.61 | 808.90 |
| 2013 | 926.39 | 484.43 | 54.57 | 1076.27 | 816.98 |
| 2014 | 919.20 | 435.90 | 0.00 | 1087.03 | 836.68 |
| 2015 | 904.88 | 380.37 | 0.00 | 1097.90 | 847.71 |
| 2016 | 897.21 | 323.99 | 0.00 | 1108.88 | 854.85 |
| 2017 | 877.95 | 260.67 | 0.00 | 1119.97 | 860.00 |
| 2018 | 858.51 | 202.12 | 0.00 | 1131.17 | 866.54 |
| 2019 | 835.95 | 162.63 | 0.00 | 1142.48 | 873.82 |
| 2020 | 810.57 | 117.79 | 0.00 | 1153.90 | 881.16 |

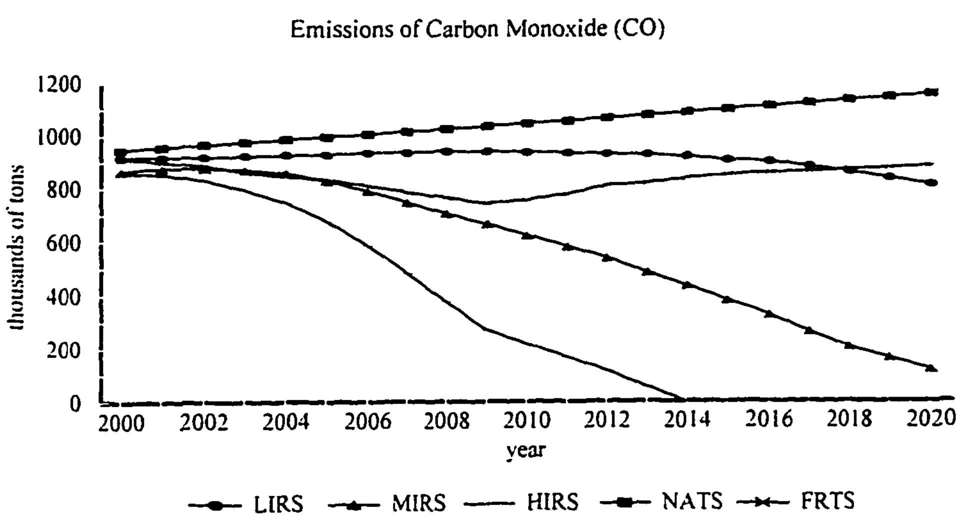


Figure 4.2 Emissions of Carbon Monoxide from Private Vehicles.

Table 4.8 Emissions of Nitrogen Oxides from Private Vehicles.

| YEAR | NOx (thousand of tons) | | | | |
|---|---|---|---|---|---|
| | LIRS | MIRS | HIRS | NATS | FRTS |
| 2000 | 47.48 | 44.28 | 44.08 | 47.86 | 47.57 |
| 2001 | 47.58 | 43.92 | 43.14 | 48.34 | 47.18 |
| 2002 | 47.68 | 43.00 | 41.71 | 48.82 | 47.06 |
| 2003 | 47.94 | 41.63 | 39.66 | 49.31 | 46.95 |
| 2004 | 47.91 | 40.14 | 37.12 | 49.80 | 46.82 |
| 2005 | 48.26 | 38.22 | 33.70 | 50.30 | 46.38 |
| 2006 | 48.33 | 35.72 | 29.66 | 50.80 | 46.24 |
| 2007 | 48.48 | 32.80 | 25.15 | 51.31 | 46.09 |
| 2008 | 48.66 | 29.90 | 20.13 | 51.82 | 45.93 |
| 2009 | 48.62 | 26.80 | 14.66 | 52.34 | 45.45 |
| 2010 | 48.65 | 23.74 | 11.55 | 52.86 | 45.90 |
| 2011 | 48.18 | 20.68 | 8.49 | 53.39 | 47.32 |
| 2012 | 47.80 | 17.78 | 5.53 | 53.93 | 48.76 |
| 2013 | 47.47 | 14.72 | 2.53 | 54.47 | 49.25 |
| 2014 | 46.92 | 12.19 | 0.00 | 55.01 | 50.40 |
| 2015 | 45.89 | 9.93 | 0.00 | 55.56 | 51.24 |
| 2016 | 44.90 | 8.01 | 0.00 | 56.12 | 51.75 |
| 2017 | 43.67 | 6.43 | 0.00 | 56.68 | 51.93 |
| 2018 | 42.23 | 4.95 | 0.00 | 57.24 | 52.45 |
| 2019 | 40.79 | 3.42 | 0.00 | 57.82 | 52.97 |
| 2020 | 39.11 | 2.40 | 0.00 | 58.39 | 53.15 |

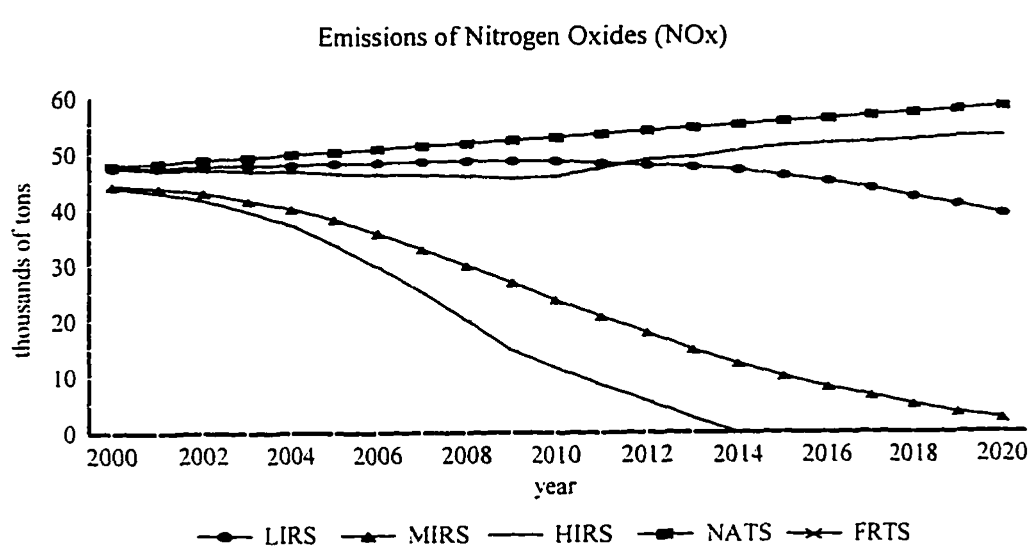


Figure 4.3 Emissions of Nitrogen Oxides from Private Vehicles.

to year 2014. After year 2014, the emissions from LIRS start decreasing notably due to the larger number of EV's introduced.

The emissions in the moderate introduction rate scenario, MIRS, are markedly lower than the emissions in the NATS from the implementation of the program, year 2000, to the end of the study, year 2020. By year 2011, the emissions in the MIRS are approximately half the emissions in the NATS. By year 2020, the emissions in the MIRS are significantly lower than the emissions in the NATS since most of the ICV's have been replaced with electric vehicles. Similar to the emissions in the MIRS, the emissions in the high introduction rate scenario, HIRS, are notably lower than the emissions in the NATS from the beginning of the program to the end. However, the emissions in the HIRS are always lower than the emissions in the MIRS. In fact, by year 2014, when the emissions in the MIRS are approximately half the emissions in the NATS, the emissions in the HIRS are zero due to the total replacement of private conventional vehicles with EV's.

The emissions in the forced retirement scenario, FRTS, show a different pattern from the pattern of the three scenarios discussed previously: LIRS, MIRS, and HIRS. During the first years, the emissions in the FRTS are slightly lower than the emissions in the NATS and the LIRS. The emissions in the FRTS decreases continuously until they reach their lowest point in year 2009. In this year, all the vehicles older than 15 years have been replaced by new ICV's. After year 2009, the emissions start to increase and their behavior becomes the same as the behavior of emissions in the no action taken scenario. That is, in year 2009, FRTS reaches its limit to reduce air pollution and, after this year, the emissions increase due to the growth of vehicles in the system, as in the NATS. The similarity of the emission patterns between the FRTS and the NATS after year 2009 are observed in Figure 4.1, 4.2, and 4.3. After year 2009, the line representing the emissions of the FRTS becomes parallel to the line representing the emissions of the NATS since these two scenarios include only ICV's and no further action to control pollution is taken in the FRTS; in other words, the FRTS reaches a steady state after year 2009.

## 4.2 Reduction of Emissions and Costs

The reduction of emissions in tons of HC, CO and $NO_x$, and the cost for each scenario are part of the results of this study. In order to discuss these results, the emissions of CO and the marginal costs in the moderate introduction rate scenario are used as an example. All the information for the rest of the pollutants and the other scenarios is presented in Appendix B. The information for all scenarios and pollutants is presented in the same order as the CO emissions and costs are discussed in this section.

Table 4.9 shows the cumulative marginal costs (in 1996 dollars) of implementing the EV's pollution control program of the moderate introduction rate scenario, MIRS, from year 2000 to year 2020. The emissions of CO in the no action taken scenario, NATS, and the emissions of CO in the MIRS are used to determine the reduction of emissions of CO. Also, the values of these emissions and the reduction of emissions are shown in Table 4.9. With this information, it is possible to find out the number of tons of CO that are reduced in a given year. For instance, in year 2010 there is a reduction of 422,292 tons of CO in the MIRS, as shown in Table 4.9. This reduction represents the emissions that are avoided in year 2010 considering that if no action is taken the emissions in year 2010 would be 1,044,610 tons. In order to calculate the cost effectiveness or the cost per ton reduced, the

Table 4.9 Reduction of CO Emissions and Its Costs (MIRS).

| YEAR | MCEV | CO | | | Cost/ton |
|---|---|---|---|---|---|
| | (billions) | (thousands of tons) | | | thds.($) |
| | | No Action | MIRS | Reduction | per ton |
| 2000 | 1.590 | 945.68 | 865.10 | 80.580 | 19.734 |
| 2001 | 3.180 | 955.13 | 876.08 | 79.055 | 40.227 |
| 2002 | 4.770 | 964.68 | 875.72 | 88.960 | 53.619 |
| 2003 | 6.360 | 974.33 | 869.52 | 104.809 | 60.682 |
| 2004 | 7.951 | 984.07 | 855.73 | 128.340 | 61.954 |
| 2005 | 9.543 | 993.92 | 826.66 | 167.257 | 57.056 |
| 2006 | 11.136 | 1003.85 | 788.86 | 214.993 | 51.799 |
| 2007 | 12.732 | 1013.89 | 744.97 | 268.921 | 47.343 |
| 2008 | 14.330 | 1024.03 | 704.65 | 319.386 | 44.867 |
| 2009 | 15.932 | 1034.27 | 664.48 | 369.787 | 43.084 |
| 2010 | 17.539 | 1044.61 | 622.32 | 422.292 | 41.533 |
| 2011 | 19.153 | 1055.06 | 580.10 | 474.965 | 40.325 |
| 2012 | 20.774 | 1065.61 | 537.97 | 527.637 | 39.371 |
| 2013 | 22.402 | 1076.27 | 484.43 | 591.834 | 37.852 |
| 2014 | 24.040 | 1087.03 | 435.90 | 651.135 | 36.919 |
| 2015 | 25.686 | 1097.90 | 380.37 | 717.533 | 35.798 |
| 2016 | 27.343 | 1108.88 | 323.99 | 784.890 | 34.836 |
| 2017 | 29.010 | 1119.97 | 260.67 | 859.300 | 33.760 |
| 2018 | 30.689 | 1131.17 | 202.12 | 929.047 | 33.033 |
| 2019 | 32.381 | 1142.48 | 162.63 | 979.854 | 33.047 |
| 2020 | 34.084 | 1153.90 | 117.79 | 1036.119 | 32.896 |

marginal costs are divided by the number of tons in a given year. The cost per ton reduced for each year is also presented in Table 4.9.

The total emissions per year of each pollutant is represented graphically and compared to the no action taken scenario. Figure 4.4 shows the CO emissions in the no action taken scenario and the CO emissions in the moderate introduction rate scenario. MIRS. The distance between the two lines is the reduction of CO emissions or the CO emissions avoided in thousand of tons. In general, the pattern that the emission lines follows is similar for all pollutants in the LIRS, MIRS and HIRS (see Appendix B). The emission lines decrease continuously from year 2000 to year 2020. In the LIRS, the emissions increase during the first 10 years, but after this period the emissions decrease continuously as in the MIRS and HIRS. The reason the emissions in the LIRS increase during the early implementation period is the significant difference between the large number of new ICV's and the small number of EV's introduced during this period.

The reduction of emissions in the forced retirement scenario, FRTS, follows a different pattern from the reductions in the LIRS, MIRS, and HIRS. In the FRTS, the emissions decrease continuously form year 2000 to year 2009. However, after year 2009 the emissions increase again and the amount of reduction becomes constant since the emissions lines in the NATS and FRTS become parallel. Overall, in the FRTS, the level of emissions in year 2020 is close or higher than the level of emissions at the beginning of the program, year 2000 (see Appendix B).

Figure 4.5 shows the relationship between the reduction of CO emissions and its cost. The reduction of emissions is given in thousand of tons and the costs in billions of

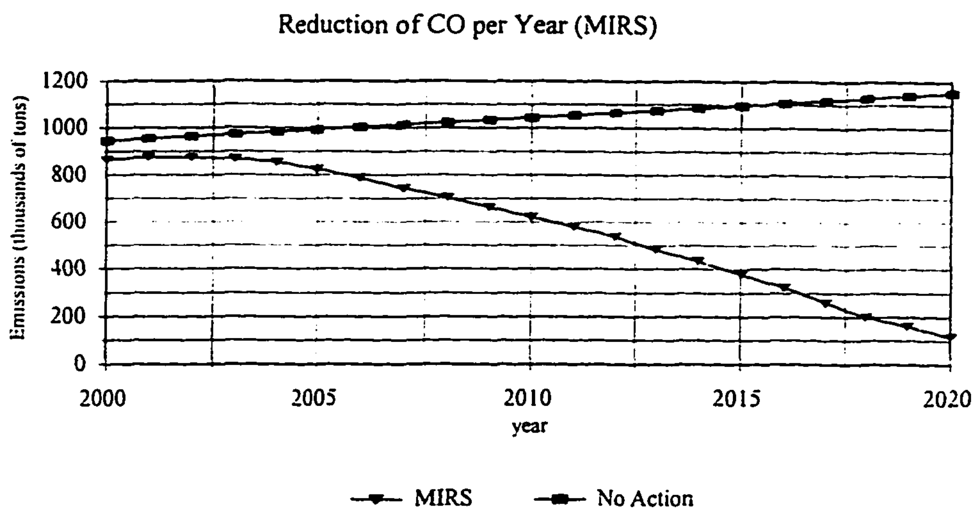


Figure 4.4 Reduction of CO Emissions for MIRS.

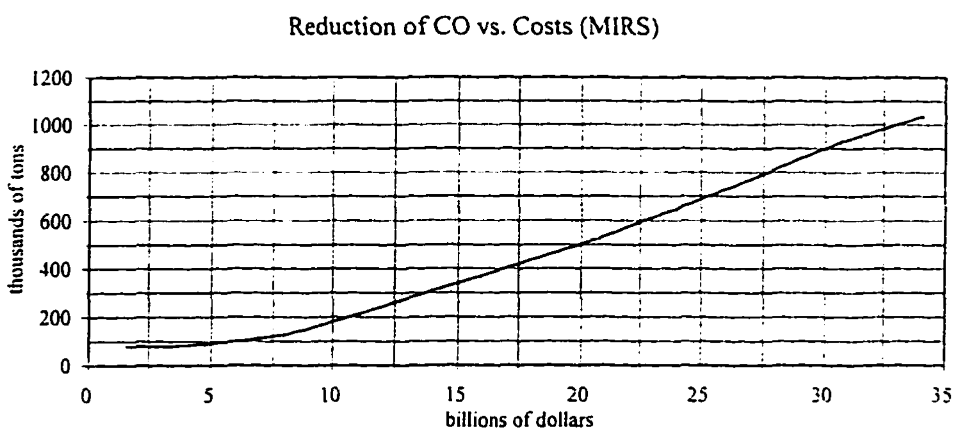


Figure 4.5 Reduction of CO vs. Costs for MIRS.

1996 dollars. Generally, for all scenarios, when the reduction of emissions increases the cost of reduction increases.

In the high introduction rate scenario, HIRS, and forced retirement scenario, FRTS, the reduction of emissions becomes smaller and the costs higher when the limit of these programs is reached. That is, when all the ICV's have been replaced with EV's and all of the oldest vehicles have been replaced with new ICV's in the HIRS and FRTS, respectively, the reduction of emissions after this point is minimal since the programs have already finished. It is expected that the same phenomenon will happen in the LIRS and MIRS after all the ICV's are replaced with EV's. However, it can not be observed in this study since all the ICV's in the system in the LIRS and MIRS are not replaced within the 20-year period of this analysis.

The cost effectiveness of reducing CO emissions per year in the MIRS is presented in Figure 4.6. The ratio of cumulative costs per ton in thousands of dollars per ton (cost effectiveness) against time is presented graphically for all scenarios (see Appendix B). Overall, the cost per ton is significantly higher during the first seven years of implementation than afterwards in the LIRS, MIRS and HIRS. The high costs during the first years in the LIRS and MIRS are caused by the small number of old ICV's replaced. That is, the programs in these two scenarios do not consider the replacement of old ICV's; they substitute exclusively part of the new ICV's or the total number of new ICV's introduced per year. Since the newer vehicle generate less pollution than the older vehicles, the reduction of emissions during the first years is low. As a result, the cost per ton reduced is high. In the HIRS, there is replacement of old ICV's with EV's; nevertheless, the cost

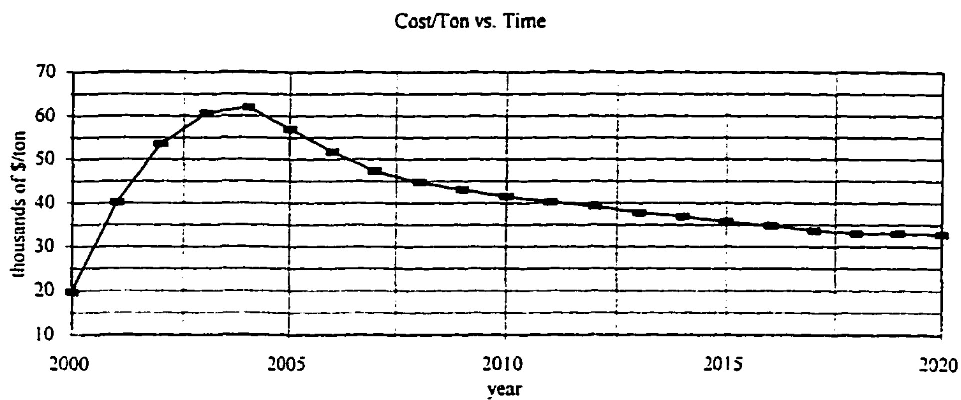


Figure 4.6 Cost Effectiveness of CO Reduction for MIRS.

per ton reduced is also high during the first years due to the small number of old ICV's replaced in this period.

In contrast, in the forced retirement scenario, FRTS, the cost per ton reduced is low during the first years due to the small number of new ICV's that have to be introduced to replace the oldest ICV's in this period. Since in the FRTS there is no introduction of EV's and the marginal cost basically depend on the number of new ICV's introduced to replace old ICV's, the costs during the first years are relatively low.

The yearly marginal cost of each scenario is presented in Table 4.10. These yearly costs represent the extra 1996 dollars that have to be invested per year in order to reduce the levels of emissions of HC, CO, and $NO_x$ for each scenario. The reduction of emissions per year for each scenario was discussed previously in this section and is presented in tables and figures in Appendix B. The yearly costs in the LIRS are relatively low during the first years as shown in Figure 4.7. However, after year 2010, the costs increase faster and continuously due to the greater number of EV's introduced in later years. In the MIRS, the yearly costs remain approximately constant during the 20-year period of this study, the costs vary from 1.26 billion in year 2000 to 1.34 billion in year 2020. In Figure 4.7 the lines representing the yearly costs in the HIRS and FRTS, follow a particular pattern. In these two scenarios the yearly costs increase continuously until year 2009, when all of the oldest ICV's have been replaced. After this point, the yearly costs reduce notably and remain constant until the end of the program, when all the ICV's have been replaced in year 2014 in the HIRS case. After year 2014, the yearly costs in the HIRS represent the costs incurred only by the EV's introduced to satisfy the vehicle growth. The yearlycosts

Table 4.10 Yearly Marginal Costs of All Scenarios.

| | MCVY (billions of 1996 dollars) | | | |
|---|---|---|---|---|
| YEAR | LIRS | MIRS | HIRS | FRTS |
| 2000 | 0.032 | 1.590 | 1.655 | 0.107 |
| 2001 | 0.032 | 1.590 | 1.696 | 0.278 |
| 2002 | 0.032 | 1.590 | 1.732 | 0.396 |
| 2003 | 0.080 | 1.590 | 1.764 | 0.492 |
| 2004 | 0.080 | 1.591 | 1.789 | 0.567 |
| 2005 | 0.162 | 1.592 | 1.854 | 0.693 |
| 2006 | 0.162 | 1.593 | 1.889 | 0.824 |
| 2007 | 0.246 | 1.595 | 1.938 | 0.917 |
| 2008 | 0.248 | 1.598 | 2.003 | 1.048 |
| 2009 | 0.334 | 1.602 | 2.114 | 1.268 |
| 2010 | 0.421 | 1.607 | 1.712 | 0.706 |
| 2011 | 0.509 | 1.614 | 1.732 | 0.706 |
| 2012 | 0.597 | 1.621 | 1.748 | 0.706 |
| 2013 | 0.686 | 1.629 | 1.760 | 0.706 |
| 2014 | 0.777 | 1.637 | 1.791 | 0.706 |
| 2015 | 0.868 | 1.647 | 1.373 | 0.819 |
| 2016 | 0.965 | 1.656 | 1.466 | 0.843 |
| 2017 | 1.060 | 1.668 | 1.515 | 0.865 |
| 2018 | 1.157 | 1.679 | 1.534 | 0.886 |
| 2019 | 1.253 | 1.691 | 1.562 | 0.901 |
| 2020 | 1.354 | 1.703 | 1.608 | 0.940 |

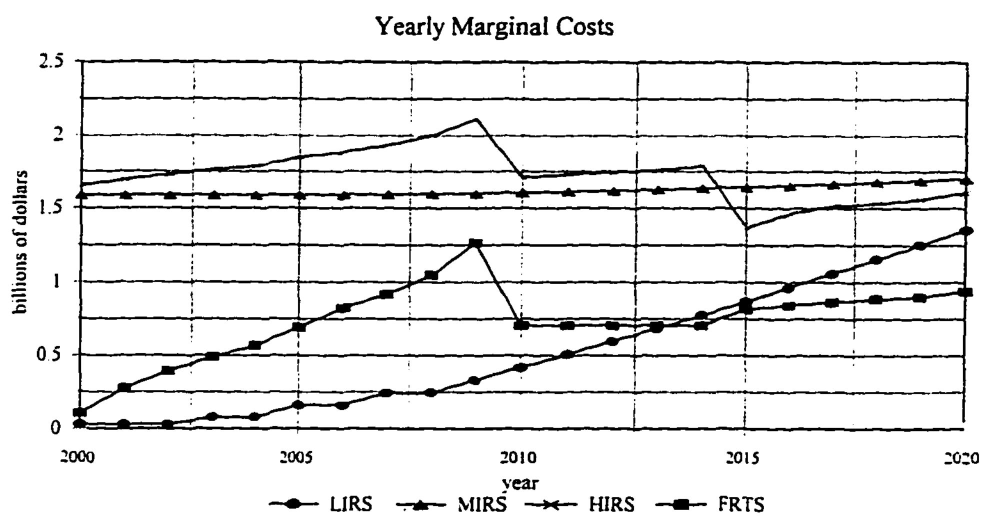


Figure 4.7 Yearly Marginal Costs of All Scenarios.

in the FRTS after year 2014 represent the costs incurred by the new ICV's introduced to satisfy the vehicle growth and replaced the ICV's older than 15 years.

### 4.3 Reduction of Pollution (% of Total ) and Concentrations

In order to determine the global impact of EV's on the air quality of Mexico City and its Metropolitan Area (MCMA), the percentage of the total reduction of emissions caused by the implementation of EV's pollution control programs was determined. Tables 4.11, 4.12 and 4.13 show the total percentage of reduction of HC, CO, and $NO_x$ for each scenario, respectively. The maximum percentage of total pollution that can be reduced depends on the total contribution of emissions generated by private vehicles. These percentages are 30.6%, 53.11%, and 30.71% for HC, CO, and $NO_x$, respectively, based on the 1995 emissions inventory of the MCMA (DDF 1996). These percentages are not reached by any of the scenarios during the 20-year period of this study, except by the high introduction rate scenario, HIRS. The maximum percentage of emissions that can be reduced by replacing all the ICV's in the system with EV's is reached by the HIRS in year 2014.

The reduction of air pollutant concentrations was determined in order to assess the benefits of the EV's pollution control programs. The concentration of pollutants (IMECAS) is determined based on the percentage of total reduction of emissions of each pollutant, as explained in section 3.3.10. Tables 4.14 and 4.15 show the reduction of CO and ozone in IMECAS points. The maximum number of IMECAS points of CO and ozone that can be reduced by replacing all the EV's with ICV's are 40.89 and 77.24, respectively. These values correspond to the reduction of CO and ozone in the HIRS after year 2014.

Table 4.11 Reduction of HC (% of Total).

| YEAR | LIRS | MIRS | HIRS | FRTS |
|---|---|---|---|---|
| 2000 | 0.11% | 2.23% | 2.45% | 0.23% |
| 2001 | 0.34% | 2.98% | 3.73% | 0.80% |
| 2002 | 0.56% | 3.85% | 5.20% | 1.37% |
| 2003 | 0.75% | 4.65% | 6.90% | 2.22% |
| 2004 | 0.93% | 5.51% | 8.73% | 2.97% |
| 2005 | 1.19% | 6.68% | 11.06% | 3.65% |
| 2006 | 1.32% | 8.01% | 13.73% | 4.39% |
| 2007 | 1.64% | 9.47% | 16.66% | 5.13% |
| 2008 | 1.83% | 10.84% | 19.59% | 5.76% |
| 2009 | 2.19% | 12.17% | 22.60% | 6.50% |
| 2010 | 2.57% | 13.51% | 24.10% | 6.39% |
| 2011 | 3.01% | 14.87% | 25.56% | 6.10% |
| 2012 | 3.45% | 16.20% | 27.01% | 5.93% |
| 2013 | 3.92% | 17.69% | 28.57% | 5.65% |
| 2014 | 4.50% | 18.89% | 30.06% | 5.30% |
| 2015 | 5.23% | 20.63% | 30.06% | 5.25% |
| 2016 | 5.78% | 22.06% | 30.06% | 5.25% |
| 2017 | 6.62% | 23.50% | 30.06% | 5.25% |
| 2018 | 7.49% | 24.83% | 30.06% | 5.30% |
| 2019 | 8.40% | 26.01% | 30.06% | 5.36% |
| 2020 | 9.37% | 27.17% | 30.06% | 5.36% |

Table 4.12 Reduction of CO (% of Total).

| YEAR | LIRS | MIRS | HIRS | FRTS |
|---|---|---|---|---|
| 2000 | 1.60% | 4.53% | 4.96% | 1.82% |
| 2001 | 2.09% | 4.40% | 5.72% | 3.09% |
| 2002 | 2.60% | 4.90% | 7.43% | 4.41% |
| 2003 | 2.89% | 5.71% | 9.89% | 6.13% |
| 2004 | 3.26% | 6.93% | 12.94% | 7.58% |
| 2005 | 3.60% | 8.94% | 16.98% | 8.74% |
| 2006 | 3.73% | 11.37% | 22.17% | 10.36% |
| 2007 | 4.21% | 14.09% | 27.95% | 12.09% |
| 2008 | 4.39% | 16.56% | 33.54% | 13.45% |
| 2009 | 4.98% | 18.99% | 39.29% | 15.03% |
| 2010 | 5.51% | 21.47% | 42.05% | 14.76% |
| 2011 | 6.16% | 23.91% | 44.73% | 13.99% |
| 2012 | 6.81% | 26.30% | 47.37% | 12.79% |
| 2013 | 7.40% | 29.20% | 50.42% | 12.79% |
| 2014 | 8.20% | 31.81% | 53.11% | 12.23% |
| 2015 | 9.34% | 34.71% | 53.11% | 12.10% |
| 2016 | 10.14% | 37.59% | 53.11% | 12.17% |
| 2017 | 11.48% | 40.75% | 53.11% | 12.33% |
| 2018 | 12.80% | 43.62% | 53.11% | 12.42% |
| 2019 | 14.25% | 45.55% | 53.11% | 12.49% |
| 2020 | 15.80% | 47.69% | 53.11% | 12.55% |

Table 4.13 Reduction of $NO_x$ (% of Total).

| Year | LIRS | MIRS | HIRS | FRTS |
|---|---|---|---|---|
| 2000 | 0.24% | 2.30% | 2.42% | 0.18% |
| 2001 | 0.48% | 2.80% | 3.30% | 0.74% |
| 2002 | 0.72% | 3.66% | 4.47% | 1.10% |
| 2003 | 0.85% | 4.78% | 6.01% | 1.47% |
| 2004 | 1.16% | 5.96% | 7.82% | 1.84% |
| 2005 | 1.24% | 7.37% | 10.13% | 2.39% |
| 2006 | 1.49% | 9.12% | 12.78% | 2.76% |
| 2007 | 1.69% | 11.08% | 15.66% | 3.13% |
| 2008 | 1.88% | 12.99% | 18.78% | 3.49% |
| 2009 | 2.19% | 14.99% | 22.11% | 4.05% |
| 2010 | 2.45% | 16.92% | 24.00% | 4.05% |
| 2011 | 3.00% | 18.82% | 25.83% | 3.49% |
| 2012 | 3.49% | 20.59% | 27.56% | 2.94% |
| 2013 | 3.94% | 22.41% | 29.29% | 2.94% |
| 2014 | 4.52% | 23.90% | 30.71% | 2.57% |
| 2015 | 5.34% | 25.22% | 30.71% | 2.39% |
| 2016 | 6.14% | 26.33% | 30.71% | 2.39% |
| 2017 | 7.05% | 27.23% | 30.71% | 2.57% |
| 2018 | 8.05% | 28.05% | 30.71% | 2.57% |
| 2019 | 9.04% | 28.90% | 30.71% | 2.57% |
| 2020 | 10.14% | 29.45% | 30.71% | 2.76% |

Table 4.14 Reduction of CO (IMECAS).

| YEAR | LIRS | MIRS | HIRS | FRTS |
|---|---|---|---|---|
| 2000 | 1.23 | 3.48 | 3.82 | 1.40 |
| 2001 | 1.61 | 3.38 | 4.40 | 2.38 |
| 2002 | 2.00 | 3.77 | 5.72 | 3.40 |
| 2003 | 2.22 | 4.40 | 7.62 | 4.72 |
| 2004 | 2.51 | 5.33 | 9.96 | 5.84 |
| 2005 | 2.77 | 6.88 | 13.07 | 6.73 |
| 2006 | 2.87 | 8.76 | 17.07 | 7.98 |
| 2007 | 3.24 | 10.85 | 21.52 | 9.31 |
| 2008 | 3.38 | 12.75 | 25.82 | 10.36 |
| 2009 | 3.83 | 14.62 | 30.25 | 11.57 |
| 2010 | 4.24 | 16.53 | 32.38 | 11.36 |
| 2011 | 4.74 | 18.41 | 34.44 | 10.77 |
| 2012 | 5.24 | 20.25 | 36.48 | 9.85 |
| 2013 | 5.69 | 22.49 | 38.82 | 9.85 |
| 2014 | 6.31 | 24.50 | 40.89 | 9.42 |
| 2015 | 7.19 | 26.73 | 40.89 | 9.32 |
| 2016 | 7.81 | 28.95 | 40.89 | 9.37 |
| 2017 | 8.84 | 31.38 | 40.89 | 9.49 |
| 2018 | 9.86 | 33.59 | 40.89 | 9.57 |
| 2019 | 10.97 | 35.07 | 40.89 | 9.62 |
| 2020 | 12.17 | 36.72 | 40.89 | 9.67 |

Table 4.15 Reduction of Ozone (IMECAS).

| Year | LIRS | MIRS | HIRS | FRTS |
|---|---|---|---|---|
| 2000 | 0.33 | 5.73 | 6.28 | 0.57 |
| 2001 | 0.92 | 7.59 | 9.44 | 2.03 |
| 2002 | 1.49 | 9.82 | 13.11 | 3.43 |
| 2003 | 1.96 | 11.95 | 17.41 | 5.48 |
| 2004 | 2.46 | 14.26 | 22.10 | 7.26 |
| 2005 | 3.07 | 17.33 | 28.08 | 8.98 |
| 2006 | 3.45 | 20.87 | 34.90 | 10.77 |
| 2007 | 4.22 | 24.76 | 42.40 | 12.56 |
| 2008 | 4.70 | 28.44 | 49.97 | 14.09 |
| 2009 | 5.62 | 32.04 | 57.78 | 15.93 |
| 2010 | 6.54 | 35.64 | 61.73 | 15.67 |
| 2011 | 7.70 | 39.30 | 65.60 | 14.86 |
| 2012 | 8.87 | 42.84 | 69.39 | 14.31 |
| 2013 | 10.05 | 46.75 | 73.44 | 13.66 |
| 2014 | 11.53 | 49.92 | 77.24 | 12.78 |
| 2015 | 13.44 | 54.24 | 77.24 | 12.59 |
| 2016 | 14.92 | 57.81 | 77.24 | 12.59 |
| 2017 | 17.09 | 61.36 | 77.24 | 12.65 |
| 2018 | 19.36 | 64.60 | 77.24 | 12.78 |
| 2019 | 21.72 | 67.53 | 77.24 | 12.91 |
| 2020 | 24.24 | 70.32 | 77.24 | 12.96 |

## 4.4 Benefits vs. Costs

In this section the benefits of all scenarios are presented. The benefits were determined by following the procedure explained in section 3.3.11. Tables 4.16 and 4.17 show the yearly and the cumulative benefits of each scenario, respectively. The moderate introduction rate scenario, MIRS, and the high introduction rate scenario, HIRS, are the two alternatives that offer major benefits. By the year 2020, the benefits of the low introduction rate scenario, LIRS, and forced retirement scenario, FRTS, are approximately one fourth of the benefits of the MIRS and HIRS. During the first years, the yearly benefits of the LIRS are lower than the benefits of FRTS; however, by the year 2020, the yearly benefits of the LIRS are twice the benefits of the FRTS approximately, as shown in Table 4.16.

The relationship between the benefits and the cost of each pollution control alternative is shown in Table 4.18. The numbers in this table are the results of the substraction of cumulative benefits minus cumulative marginal costs. Consequently, a negative value indicates that the benefits in a given year are lower than the costs in the same year. In contrast, a positive number indicates that the benefits are greater than the costs. The relationship between benefits and costs is presented graphically in Figure 4.8. It is observed that during the first years, the benefits of all scenarios are lower than the costs. Nevertheless, the benefits of the LIRS, MIRS and HIRS become greater than the costs, eventually, as shown in Figure 4.8. To the contrary, the benefits of the FRTS are lower than the costs throughout the 20-year period considered in this study.

Table 4.16 Yearly Benefits of All Scenarios.

| | BENEFITS (billions of 1996 dollars) | | | |
|---|---|---|---|---|
| Year | LIRS | MIRS | HIRS | FRTS |
| 2000 | 0.015 | 0.262 | 0.286 | 0.026 |
| 2001 | 0.043 | 0.353 | 0.439 | 0.094 |
| 2002 | 0.071 | 0.466 | 0.622 | 0.163 |
| 2003 | 0.095 | 0.578 | 0.843 | 0.265 |
| 2004 | 0.122 | 0.704 | 1.091 | 0.359 |
| 2005 | 0.155 | 0.873 | 1.414 | 0.452 |
| 2006 | 0.177 | 1.072 | 1.793 | 0.553 |
| 2007 | 0.221 | 1.298 | 2.222 | 0.658 |
| 2008 | 0.251 | 1.520 | 2.671 | 0.753 |
| 2009 | 0.306 | 1.747 | 3.151 | 0.869 |
| 2010 | 0.364 | 1.982 | 3.433 | 0.872 |
| 2011 | 0.437 | 2.230 | 3.721 | 0.843 |
| 2012 | 0.513 | 2.479 | 4.015 | 0.828 |
| 2013 | 0.593 | 2.759 | 4.335 | 0.806 |
| 2014 | 0.694 | 3.005 | 4.650 | 0.769 |
| 2015 | 0.825 | 3.331 | 4.743 | 0.773 |
| 2016 | 0.935 | 3.621 | 4.838 | 0.789 |
| 2017 | 1.092 | 3.920 | 4.934 | 0.808 |
| 2018 | 1.262 | 4.210 | 5.033 | 0.833 |
| 2019 | 1.444 | 4.488 | 5.134 | 0.858 |
| 2020 | 1.643 | 4.767 | 5.236 | 0.879 |

Table 4.17 Cumulative Benefits of All Scenarios.

| | Cumulative Benefits (billions of 1996 dollars) | | | |
|---|---|---|---|---|
| Year | LIRS | MIRS | HIRS | FRTS |
| 2000 | 0.015 | 0.262 | 0.286 | 0.026 |
| 2001 | 0.058 | 0.615 | 0.726 | 0.120 |
| 2002 | 0.128 | 1.081 | 1.348 | 0.283 |
| 2003 | 0.223 | 1.659 | 2.191 | 0.548 |
| 2004 | 0.345 | 2.363 | 3.282 | 0.907 |
| 2005 | 0.500 | 3.236 | 4.696 | 1.359 |
| 2006 | 0.677 | 4.309 | 6.489 | 1.912 |
| 2007 | 0.898 | 5.607 | 8.711 | 2.570 |
| 2008 | 1.149 | 7.127 | 11.383 | 3.323 |
| 2009 | 1.455 | 8.874 | 14.533 | 4.192 |
| 2010 | 1.819 | 10.856 | 17.966 | 5.063 |
| 2011 | 2.256 | 13.085 | 21.688 | 5.906 |
| 2012 | 2.769 | 15.564 | 25.703 | 6.734 |
| 2013 | 3.362 | 18.323 | 30.037 | 7.541 |
| 2014 | 4.057 | 21.328 | 34.687 | 8.310 |
| 2015 | 4.882 | 24.659 | 39.430 | 9.083 |
| 2016 | 5.816 | 28.280 | 44.267 | 9.872 |
| 2017 | 6.908 | 32.200 | 49.202 | 10.680 |
| 2018 | 8.170 | 36.409 | 54.235 | 11.512 |
| 2019 | 9.614 | 40.898 | 59.368 | 12.370 |
| 2020 | 11.257 | 45.665 | 64.605 | 13.249 |

Table 4.18 Cumulative Benefits Minus Cumulative Costs.

| YEAR | Benefits minus Costs (billions of 1996 dollars) | | | |
|---|---|---|---|---|
| | LIRS | MIRS | HIRS | FRTS |
| 2000 | -0.017 | -1.329 | -1.369 | -0.081 |
| 2001 | -0.006 | -2.565 | -2.626 | -0.265 |
| 2002 | 0.033 | -3.689 | -3.736 | -0.498 |
| 2003 | 0.048 | -4.701 | -4.657 | -0.725 |
| 2004 | 0.089 | -5.588 | -5.354 | -0.933 |
| 2005 | 0.082 | -6.307 | -5.795 | -1.173 |
| 2006 | 0.096 | -6.828 | -5.890 | -1.444 |
| 2007 | 0.071 | -7.125 | -5.606 | -1.703 |
| 2008 | 0.075 | -7.203 | -4.938 | -1.998 |
| 2009 | 0.047 | -7.058 | -3.901 | -2.398 |
| 2010 | -0.010 | -6.683 | -2.180 | -2.232 |
| 2011 | -0.082 | -6.068 | -0.191 | -2.095 |
| 2012 | -0.166 | -5.210 | 2.076 | -1.973 |
| 2013 | -0.259 | -4.079 | 4.651 | -1.873 |
| 2014 | -0.341 | -2.711 | 7.510 | -1.810 |
| 2015 | -0.384 | -1.027 | 10.880 | -1.856 |
| 2016 | -0.414 | 0.938 | 14.251 | -1.910 |
| 2017 | -0.383 | 3.190 | 17.670 | -1.967 |
| 2018 | -0.278 | 5.720 | 21.169 | -2.021 |
| 2019 | -0.087 | 8.517 | 24.740 | -2.064 |
| 2020 | 0.202 | 11.581 | 28.368 | -2.125 |

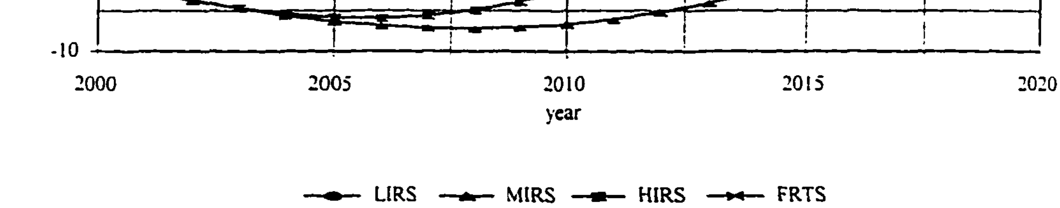


Figure 4.8 Benefits Minus Costs vs. Time.

The values obtained for the low introduction rate scenario (LIRS) in table 4.18 do not follow a pattern similar to that of the other two scenarios that consider the introduction of EV's (MIRS and HIRS). In the LIRS the cumulative benefits minus cimulative costs remain close to zero. Small fluctuations in either the cumulative benefits or cumulative costs cause the value to change from negative to positive or vice versa.

# CHAPTER 5

# CONCLUSIONS AND FUTURE RESEARCH

In this chapter, the general conclusions of this study are presented. The global study and the results obtained in specific scenarios are discussed. After the conclusions, a number of future research topics are suggested.

## 5.1 Conclusions

The purpose of this study was to design a model capable of determining the reduction of emissions per dollar invested in electric vehicles. In addition to fulfilling this objective, the model developed also allows information to be modified or adjusted to new conditions due to the flexibility of the EVCAP program which was created to simulate the dynamics of vehicles, to determine marginal costs, and to create MOBILE5 input files. Thus, if significant changes in EV's prices, battery efficiencies, and other parameters occur, the results can be readily updated. Although the model was used to determine the effects of replacing only private vehicles (ICV's) with electric vehicles or new ICV's, this model can be applied to analyze the replacement of other type of vehicles, namely public vehicles such as two passenger taxis, four passenger taxis, and mini van taxis. However, the model is limited to certain type of vehicles; for instance, the model is not capable of simulating the effects of motorcycles, heavy duty trucks, buses, and diesel vehicles without further adjustments.

The primary results of this study indicate that the use of electric vehicle by the residents of Mexico City and its Metropolitan Area (MCMA) would result in a net reduction of emissions of hydrocarbon (HC), carbon monoxide (CO) and nitrogen oxides ($NO_x$). The reduction of emissions in MCMA caused by the implementation of EV's programs would be significant due to the fact that most of the electricity consumed in MCMA is generated by power plants located outside of this region. The effects of extra emissions outside the MCMA were not considered in this study. However, the damages from one unit of pollution outside Mexico City are expected to be far less than the damages from one unit of pollution on the susceptible atmosphere of MCMA, mainly, because of Mexico City's high altitude, and the surrounding mountains. Consequently, it can be concluded that increased electric vehicle penetration will result in greater emissions reduction of HC, CO and $NO_x$.

The cost of reducing emissions (dollars per ton reduced) with EV's is still higher than the cost of other alternatives such as the use of cleaner fuels, the use of catalytic convertors, or the implementation of programs which forbid people to use their vehicles. However, the reduction of emissions offered by the latter alternatives is significantly lower than the reduction obtained with electric vehicles. That is, these alternatives do not completely eliminate the total tail pipe emissions generated by private vehicles as do EV's. In the case of the forced retirement scenario, FRTS, where the oldest vehicles are replaced with only new ICV's, the cost per ton reduced was lower than the other three scenarios that considered electric vehicles, LIRS, MIRS and HIRS. Nevertheless, when the costs of these scenarios were compared to the benefits, the benefits of the scenarios which considered EV's eventually became higher than the costs. On the other hand, the benefits of the FRTS were lower than the costs throughout the study. As a result, it can be stated that the EV's pollution control programs are expensive but more effective in the long term than the alternatives previously mentioned due to the much greater benefits offered by EV's. This situation resembles the case of two types of medicines. The first type of medicine is inexpensive but only will temporarily reduce the pain or effects of a chronic disease. The second type is expensive but will cure people of that chronic disease.

Each scenario that includes EV's, namely, LIRS, MIRS, and HIRS, has a different EV's introduction schedule; thus, the yearly costs are different for each scenario. If decision makers approve the implementation of an EV's pollution control program. The type of EV's introduction schedule will depend on the economic situation and the significance of air pollution effects on MCMA. Independent of what EV's pollution control program they may select, this study proves that the benefits of all of the EV's programs will eventually become greater than the costs. The smaller the EV's introduction rate is the longer it takes to reach the point where the benefits are greater than the costs.

This study suggests that the main factor that keeps the cost of EV's pollution control programs high are the price of EV's which is expected to be lower in the near future. Two other factors that have an important impact on the cost of EV programs are the efficiency of battery chargers and the efficiency or price of batteries. This study found that the costs of EV's programs are substantially sensitive to battery prices. Another factor that influenced the cost of EV's programs was the deterioration rate of EV's. This study indicates that better deterioration rates cause an important reduction in the costs of EV's pollution control programs. Nevertheless, although it was pointed out that EV's were more reliable than ICV's, it was assumed that the EV's deterioration rate was equal to the deterioration rate of ICV's because of the lack of historical information on the deterioration of EV's operating within a real transportation system. Thus. the future costs of EV's pollution control programs are lower than the costs used in this study.

Even though the benefits offered by the EV's programs considered in this analysis are significant, the reduction of emissions is not enough to bring down the concentration levels to permissible limits. For instance, the current average of maximum concentrations of ozone in MCMA is approximately 194 IMECAS points while the maximum reduction of ozone that can be obtained by replacing all the private vehicles from MCMA with EV's is 77 IMECAS points. Since the recommended limit is 100 IMECAS points, other type of vehicles besides private vehicles and/or the reduction of emissions from other sectors must be considered if the reduction of pollution to recommended levels is to be achieved.

## 5.2 Future Research

- It is suggested that this study be expanded to consider the effects of public vehicles such as two passenger taxis, four passenger taxis, and mini van taxis on the air quality of MCMA. In addition, the model could be modified to include more types of vehicles such as motorcycles, heavy duty trucks, buses, and diesel powered vehicles.
- In order to estimate the benefits of air pollution control programs in metropolitan areas more accurately, more research on effects of air pollutants on human health, vegetation, livestock, and materials is suggested. That is, more dose-response functions of air pollutants have to be found so that damages in significant sectors can be determined and valued. For instance, dose-response functions of air pollutants for carcinogenic effects, for more types of building materials besides steel and galvanized

metals. for public and private gardens, for aesthetic materials, and for domestic animals have to be determined.

- Research to determine the impact of electric vehicles on the electric system of MCMA is suggested. It is important to determine the effects of electric vehicles on the quality of electricity, to determine the feasibility of implementing a program to assign different electricity rates (prices) depending on the time of consumption, and to find out if EV's will increase the profits of utility companies.
- It is important to note that the benefits determined in this study do not consider other benefits that EV's offer, namely the reduction of noise and reduction of water pollution which can considerably increase the overall benefits of introducing EV's in MCMA. It is suggested that other studies be carried out to determine the benefits of reducing acoustic pollution and to determine the benefits of reducing water pollution by introducing EV's into MCMA. The reduction of water pollution refers to the elimination of dumping ICV's used motor oil since EV's do not require motor oil to operate. Dumping used oil sends oil and its contaminants into ground and surface water. The contaminants can enter the food chain at many points. In addition, films of oil on the surface of water prevent the replenishment of dissolved oxygen, impair the photosynthetic processes, and block sunlight. Used oil is slow to degrade and evaporate. Consequently, a small amount of oil seriously contaminates a large amount of drinking water. The U.S. Congress (1986) reported that "A gallon of used oil from a single oil change can ruin a million gallons of fresh water--a year's supply for 50 people."

- A study to determine the economic impact of electric vehicles on the Mexican national oil company (PEMEX) should be carried out in order to explain whether the introduction of EV's will favor the profitability of this company or not. Since the consumption of gasoline might drop significantly with the introduction of EV's, new markets for the oil surplus would have to be analyzed.

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# APPENDIX A

Table A.1 Relation of IMECAS and Reduction of Emissions (% of Total). (LANL 1994, pg. 31-33)

| Reduction of CO | | Reduction of NOx | | Reduction of Ozone | | |
|---|---|---|---|---|---|---|
| (% of total) | (Imecas) | (% of total) | (Imecas) | Ozone | HC | NOx |
| | | | | (Imecas) | (% of total) | (% of total) |
| 13.69 | 10.54 | 0.00 | 0.00 | 14.88 | 6.58 | 0.00 |
| 0.00 | 0.00 | 0.16 | 0.12 | 0.05 | 0.00 | 0.16 |
| 0.00 | 0.00 | 0.68 | 0.50 | 0.20 | 0.00 | 0.68 |
| 0.50 | 0.39 | -0.05 | -0.04 | 0.61 | 0.28 | -0.05 |
| 1.80 | 1.39 | 0.35 | 0.26 | 1.98 | 0.83 | 0.35 |
| 4.93 | 3.80 | 0.00 | 0.00 | 14.12 | 6.24 | 0.00 |
| 7.01 | 5.40 | 1.47 | 1.09 | 7.96 | 3.32 | 1.47 |
| 3.06 | 2.36 | 0.13 | 0.09 | 3.07 | 1.34 | 0.13 |
| 7.72 | 5.95 | 2.15 | 1.59 | 8.31 | 3.40 | 2.15 |
| 0.00 | 0.00 | 3.63 | 2.68 | 1.06 | 0.00 | 3.63 |
| 0.20 | 0.15 | 0.05 | 0.03 | 0.01 | 0.00 | 0.05 |
| 0.01 | 0.01 | 6.46 | 4.78 | 1.96 | 0.03 | 6.46 |
| 0.00 | 0.00 | -2.00 | -1.48 | -0.59 | 0.00 | -2.00 |
| 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 0.10 | 0.08 | 0.00 | 0.00 | 0.63 | 0.28 | 0.00 |
| 0.60 | 0.47 | 0.40 | 0.29 | 2.98 | 1.26 | 0.40 |
| 0.00 | 0.00 | 0.00 | 0.00 | 5.49 | 2.43 | 0.00 |
| 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 0.00 | 0.00 | 0.00 | 0.00 | 8.17 | 3.61 | 0.00 |
| 0.08 | 0.06 | 0.03 | 0.02 | 0.09 | 0.04 | 0.03 |
| 0.31 | 0.24 | 0.11 | 0.08 | 0.39 | 0.16 | 0.11 |
| 0.16 | 0.12 | 0.02 | 0.01 | 0.14 | 0.06 | 0.02 |
| 2.00 | 1.54 | 0.87 | 0.64 | 2.37 | 0.93 | 0.87 |
| 0.01 | 0.01 | 0.00 | 0.00 | 0.01 | 0.00 | 0.00 |
| 0.93 | 0.72 | 0.11 | 0.08 | 1.28 | 0.55 | 0.11 |
| 0.18 | 0.13 | 0.07 | 0.05 | 0.31 | 0.13 | 0.07 |
| 0.71 | 0.54 | 0.62 | 0.46 | 1.25 | 0.47 | 0.62 |
| 0.14 | 0.11 | 0.38 | 0.28 | 0.40 | 0.13 | 0.38 |
| 0.89 | 0.69 | 0.44 | 0.33 | 1.25 | 0.49 | 0.44 |
| 0.00 | 0.00 | 0.00 | 0.00 | 6.92 | 3.06 | 0.00 |
| 0.00 | 0.00 | 0.00 | 0.00 | 1.74 | 0.77 | 0.00 |
| 0.10 | 0.08 | 0.05 | 0.17 | 0.17 | 0.07 | 0.05 |
| 38.62 | 29.73 | 11.90 | 8.80 | 47.44 | 19.43 | 11.90 |
| 9.36 | 7.20 | 1.08 | 0.80 | 10.14 | 4.34 | 1.08 |
| 26.85 | 20.68 | 5.61 | 4.15 | 26.21 | 10.86 | 5.61 |
| 9.42 | 7.52 | 1.98 | 1.47 | 9.07 | 3.75 | 1.98 |
| 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |

Results obtained for a group of alternatives to reduce air pollution in Mexico City and Its Metropolitan Area.

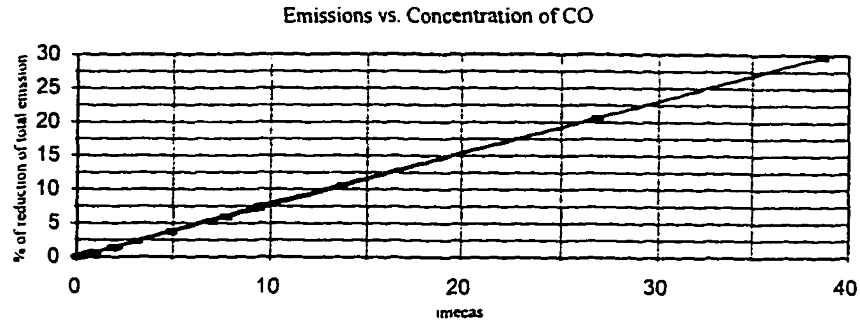


Figure A.1 Reduction of CO Emissions vs. IMECAS of CO.

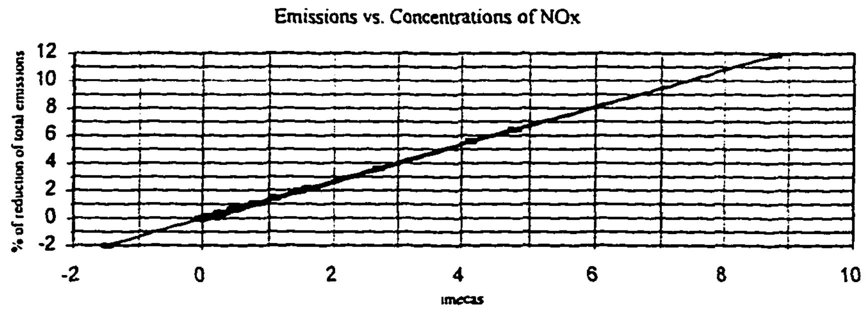


Figure A.2 Reduction of $NO_x$ Emissions vs. IMECAS of $NO_x$.

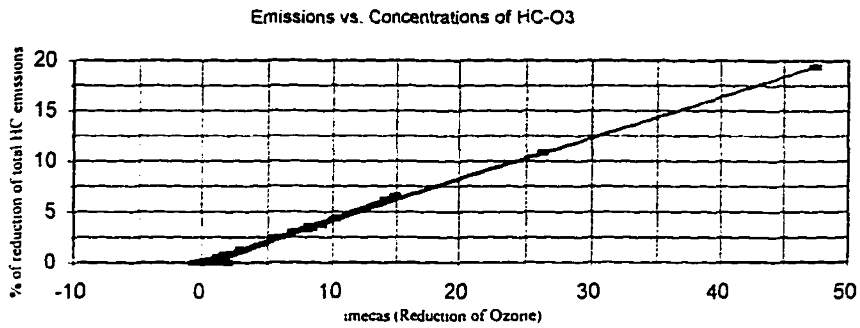


Figure A.3 Reduction of HC Emissions vs. IMECAS of Ozone.

Table A.2 Relationship Between Reduction of CO Emissions and IMECAS.

| CO Regression Output: | |
|---|---|
| Constant | 0.0056 |
| Std Err of Y Est | 0.0442 |
| R Squared | 0.9999 |
| No. of Observations | 37.0000 |
| Degrees of Freedom | 35.0000 |
| X Coefficient(s) | 0.7706 |
| Std Err of Coef. | 0.0009 |
| Imecas = (0.77) * (% of total reduction of emissions) | |

Table A.3 Relationship Between Reduction of $NO_x$ Emissions and IMECAS.

| NOx Regression Output: | |
|---|---|
| Constant | 0.0034 |
| Std Err of Y Est | 0.0224 |
| R Squared | 0.9998 |
| No. of Observations | 37.0000 |
| Degrees of Freedom | 35.0000 |
| X Coefficient(s) | 0.7391 |
| Std Err of Coef. | 0.0015 |
| Imecas = (0.74) * (% of total reduction of emissions) | |

Table A.4 Reduction of HC & $NO_x$ Emissions and Ozone (IMECAS).

| Ozone Regression Output: | | |
|---|---|---|
| Constant | | 0.0003 |
| Std Err of Y Est | | 0.0068 |
| R Squared | | 1.0000 |
| No. of Observations | | 37.0000 |
| Degrees of Freedom | | 34.0000 |
| X Coefficient(s) | 2.2623 | 0.2929 |
| Std Err of Coef. | 0.0004 | 0.0007 |
| Imecas (Ozone) = 2.263 * RHC + 0.3 * RNOx | | |
| where: | | |
| RHC= Reduction of HC Emissions (% of Total) | | |
| RNOx= Reduction of NOx Emissions (% of Total) | | |

Table A.5 Methods of Calculating IMECA Values for the Pollutants. (LANL 1994, pg. 19).

| Pollutant | Concentration Interval | Equation |
|---|---|---|
| Particulates (Pst) | 0-275 $\mu g/M^3$<br>275-100 $\mu g/M^3$ | IMECA=0.36363636*C(Pst)<br>IMECA= 0.55172413*C(Pst)-51.72413 |
| $SO_2$ | 0-0.13 PPM<br>0.13-1 PPM | IMECA= 769.230769*C($SO_2$)<br>IMECA=459.770114*C($SO_2$)+40.22989 |
| CO | 0-13 PPM<br>13-50 PPM | IMECA= 7.69230768*C(CO)<br>IMECA= 10.8108108*C(CO)-40.5405 |
| $NO_2$ | 0-0.21 PPM<br>0.21-2 PPM | IMECA= 476.190476*C($NO_2$)<br>IMECA= 223.463687*C($NO_2$)+53.07264 |
| $O_3$ | 0-0.11 PPM<br>0.11-0.6 PPM | IMECA= 909.090909*C($O_3$)+5<br>IMECA= 816.326350*C($O_3$)+10.20409 |

*Where: C(x) is the concentration of the pollutants.

# APPENDIX B

Table B.1 Reduction of HC Emissions and Its Cost (LIRS).

| YEAR | MCEV | HC | | | Cost/ton |
|---|---|---|---|---|---|
| | (billions) | (thousands of tons) | | | thds. ($) |
| | | No Action | LIRS | Reduction | per ton |
| 2000 | 0.032 | 151.02 | 150.44 | 0.58 | 55.089 |
| 2001 | 0.064 | 152.53 | 150.80 | 1.73 | 36.796 |
| 2002 | 0.095 | 154.06 | 151.17 | 2.88 | 33.084 |
| 2003 | 0.176 | 155.60 | 151.71 | 3.89 | 45.153 |
| 2004 | 0.256 | 157.15 | 152.27 | 4.89 | 52.364 |
| 2005 | 0.418 | 158.73 | 152.43 | 6.30 | 66.378 |
| 2006 | 0.580 | 160.31 | 153.25 | 7.07 | 82.145 |
| 2007 | 0.827 | 161.92 | 153.08 | 8.84 | 93.509 |
| 2008 | 1.074 | 163.53 | 153.60 | 9.94 | 108.075 |
| 2009 | 1.408 | 165.17 | 153.12 | 12.05 | 116.913 |
| 2010 | 1.829 | 166.82 | 152.58 | 14.25 | 128.428 |
| 2011 | 2.339 | 168.49 | 151.64 | 16.85 | 138.762 |
| 2012 | 2.935 | 170.17 | 150.62 | 19.56 | 150.082 |
| 2013 | 3.621 | 171.88 | 149.47 | 22.41 | 161.627 |
| 2014 | 4.398 | 173.60 | 147.62 | 25.98 | 169.311 |
| 2015 | 5.266 | 175.33 | 144.82 | 30.51 | 172.612 |
| 2016 | 6.231 | 177.08 | 143.03 | 34.05 | 182.982 |
| 2017 | 7.291 | 178.86 | 139.48 | 39.38 | 185.154 |
| 2018 | 8.448 | 180.64 | 135.64 | 45.01 | 187.698 |
| 2019 | 9.701 | 182.45 | 131.47 | 50.98 | 190.284 |
| 2020 | 11.055 | 184.28 | 126.86 | 57.42 | 192.534 |

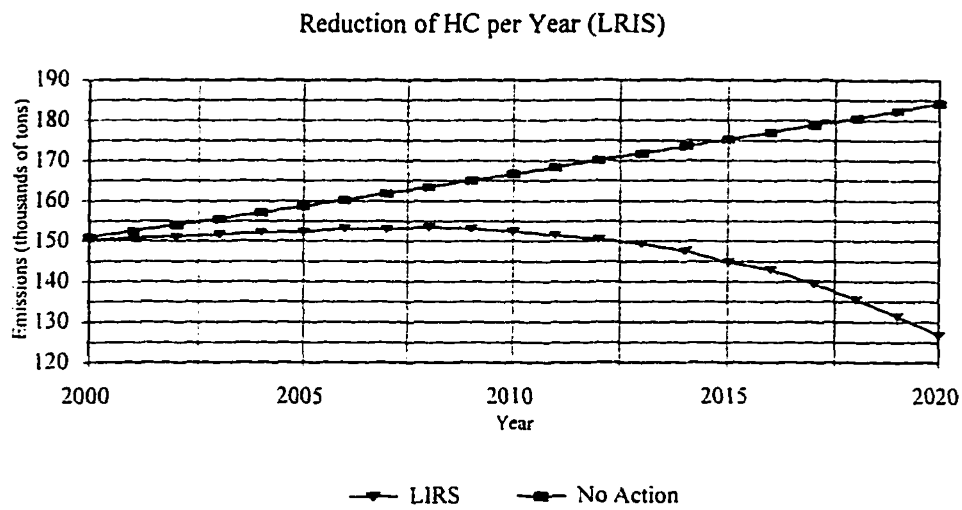


Figure B.1 Reduction of HC Emissions for LIRS.

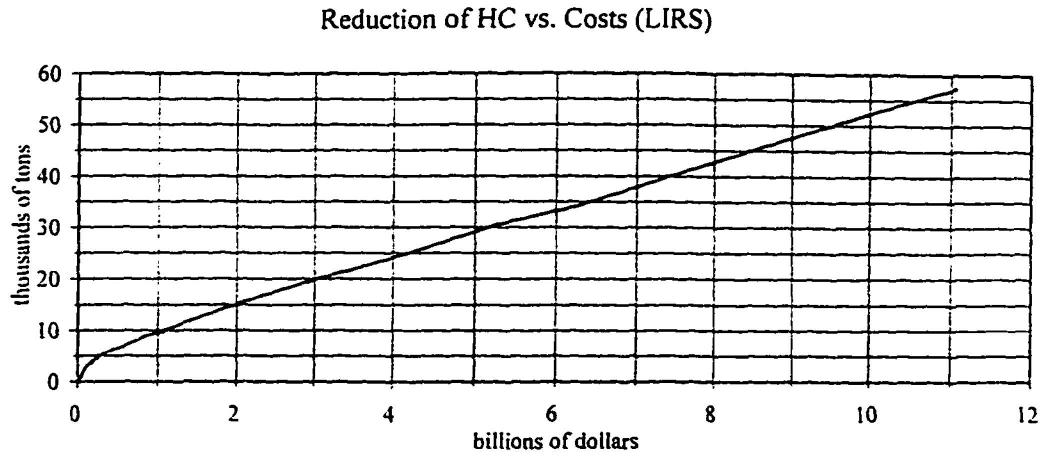


Figure B.2 Reduction of HC vs. Costs for LIRS.

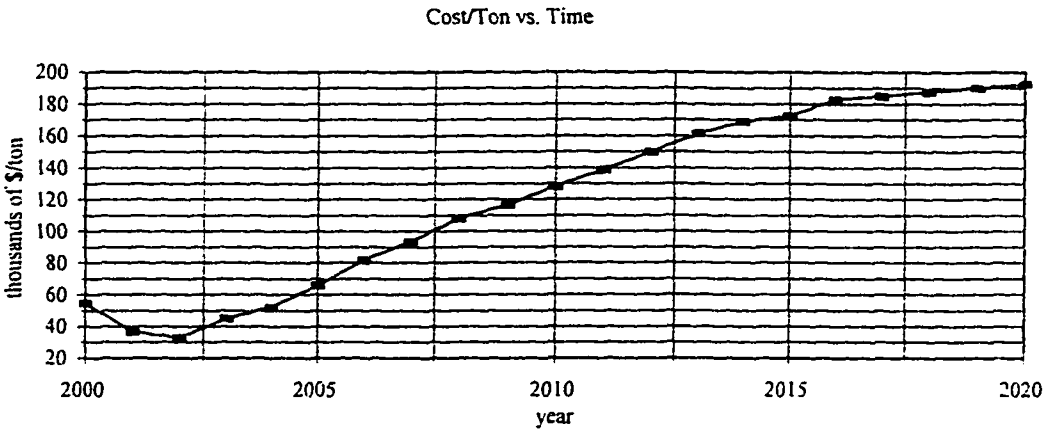


Figure B.3 Cost Efectivness of HC Reduction for LIRS.

Table B.2 Reduction of CO Emissions and Its Costs (LIRS).

| YEAR | MCEV | CO | | | Cost/ton |
|---|---|---|---|---|---|
| | (billions) | (thousands of tons) | | | thds. ($) |
| | | No Action | LIRS | Reduction | per ton |
| 2000 | 0.032 | 945.68 | 917.25 | 28.423 | 1.119 |
| 2001 | 0.064 | 955.13 | 917.51 | 37.625 | 1.690 |
| 2002 | 0.095 | 964.68 | 917.51 | 47.176 | 2.022 |
| 2003 | 0.176 | 974.33 | 921.35 | 52.981 | 3.316 |
| 2004 | 0.256 | 984.07 | 923.59 | 60.480 | 4.231 |
| 2005 | 0.418 | 993.92 | 926.64 | 67.278 | 6.212 |
| 2006 | 0.580 | 1003.85 | 933.33 | 70.525 | 8.230 |
| 2007 | 0.827 | 1013.89 | 933.44 | 80.452 | 10.274 |
| 2008 | 1.074 | 1024.03 | 939.45 | 84.578 | 12.700 |
| 2009 | 1.408 | 1034.27 | 937.38 | 96.894 | 14.534 |
| 2010 | 1.829 | 1044.61 | 936.19 | 108.427 | 16.873 |
| 2011 | 2.339 | 1055.06 | 932.78 | 122.279 | 19.124 |
| 2012 | 2.935 | 1065.61 | 928.99 | 136.625 | 21.485 |
| 2013 | 3.621 | 1076.27 | 926.39 | 149.874 | 24.163 |
| 2014 | 4.398 | 1087.03 | 919.20 | 167.833 | 26.204 |
| 2015 | 5.266 | 1097.90 | 904.88 | 193.016 | 27.284 |
| 2016 | 6.231 | 1108.88 | 897.21 | 211.674 | 29.436 |
| 2017 | 7.291 | 1119.97 | 877.95 | 242.017 | 30.127 |
| 2018 | 8.448 | 1131.17 | 858.51 | 272.655 | 30.983 |
| 2019 | 9.701 | 1142.48 | 835.95 | 306.533 | 31.648 |
| 2020 | 11.055 | 1153.90 | 810.57 | 343.334 | 32.199 |

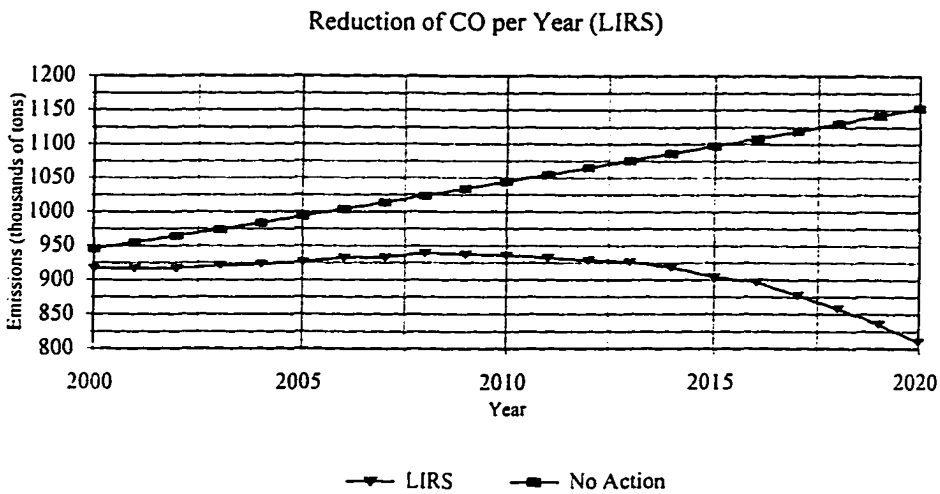


Figure B.4 Reduction of CO Emissions per Year (LIRS).

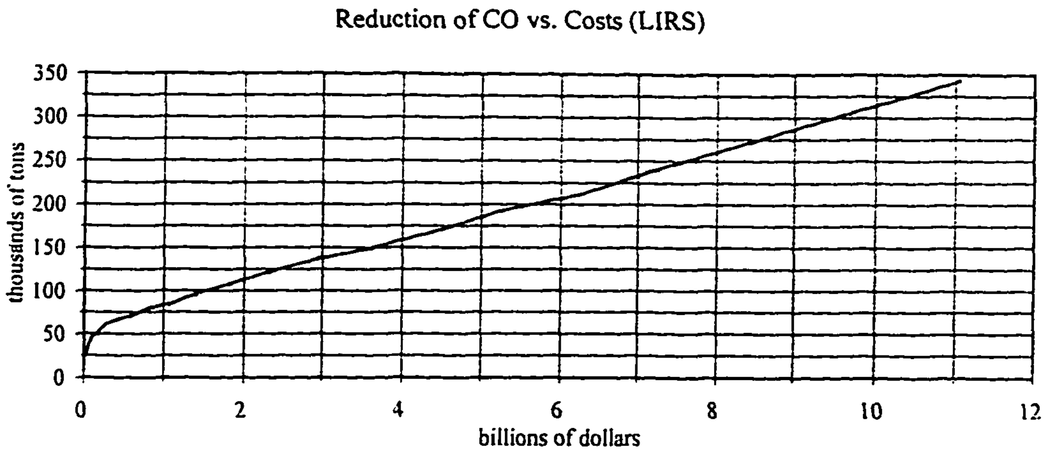


Figure B.5 Reduction of CO vs. Costs for LIRS.

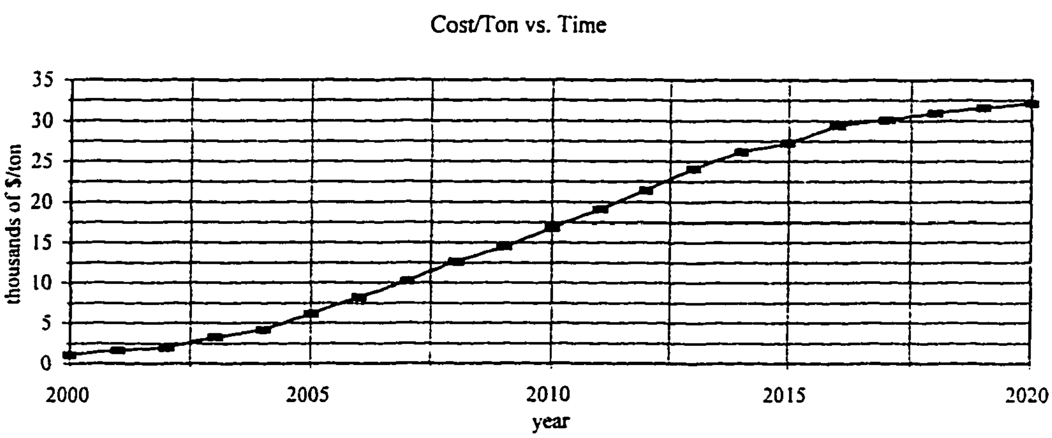


Figure B.6 Cost Efectiveness of CO Reduction for LIRS.

Table B.3 Reduction of NOx Emissions and Its Costs (LIRS).

| YEAR | MCEV | NOx | | | Cost/ton |
|---|---|---|---|---|---|
| | (billions) | (thousands of tons) | | | thds.($) |
| | | No Action | LIRS | Reduction | per ton |
| 2000 | 0.032 | 47.86 | 47.48 | 0.378 | 84.063 |
| 2001 | 0.064 | 48.34 | 47.58 | 0.759 | 83.804 |
| 2002 | 0.095 | 48.82 | 47.68 | 1.141 | 83.607 |
| 2003 | 0.176 | 49.31 | 47.94 | 1.369 | 128.342 |
| 2004 | 0.256 | 49.80 | 47.91 | 1.886 | 135.681 |
| 2005 | 0.418 | 50.30 | 48.26 | 2.039 | 204.995 |
| 2006 | 0.580 | 50.80 | 48.33 | 2.470 | 235.039 |
| 2007 | 0.827 | 51.31 | 48.48 | 2.830 | 292.063 |
| 2008 | 1.074 | 51.82 | 48.66 | 3.164 | 339.493 |
| 2009 | 1.408 | 52.34 | 48.62 | 3.725 | 378.079 |
| 2010 | 1.829 | 52.86 | 48.65 | 4.212 | 434.347 |
| 2011 | 2.339 | 53.39 | 48.18 | 5.209 | 448.966 |
| 2012 | 2.935 | 53.93 | 47.80 | 6.129 | 478.910 |
| 2013 | 3.621 | 54.47 | 47.47 | 6.993 | 517.855 |
| 2014 | 4.398 | 55.01 | 46.92 | 8.088 | 543.744 |
| 2015 | 5.266 | 55.56 | 45.89 | 9.666 | 544.819 |
| 2016 | 6.231 | 56.12 | 44.90 | 11.219 | 555.391 |
| 2017 | 7.291 | 56.68 | 43.67 | 13.003 | 560.742 |
| 2018 | 8.448 | 57.24 | 42.23 | 15.011 | 562.768 |
| 2019 | 9.701 | 57.82 | 40.79 | 17.023 | 569.877 |
| 2020 | 11.055 | 58.39 | 39.11 | 19.285 | 573.232 |

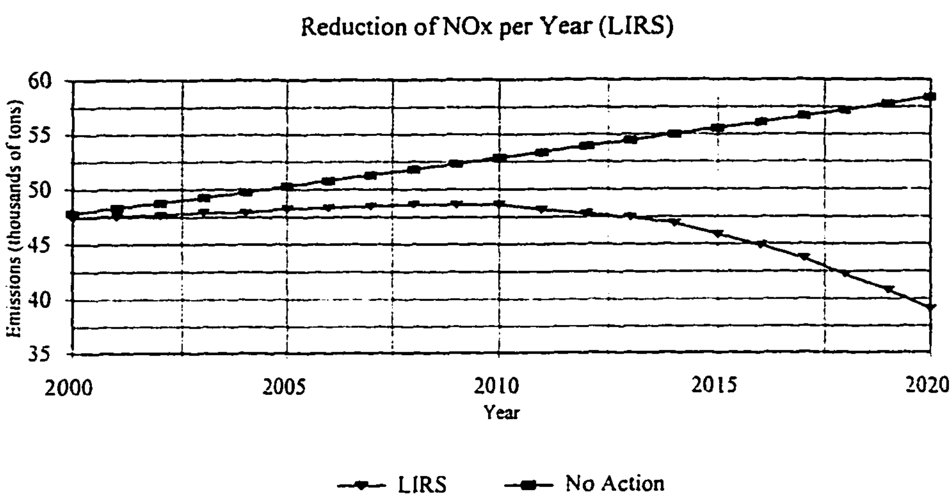


Figure B.7 Reduction of NOx Emissions for LIRS.

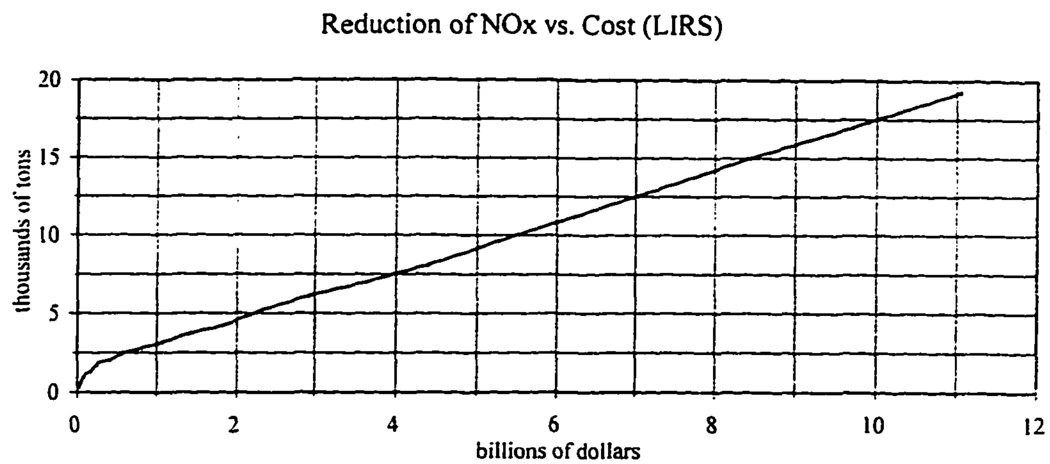


Figure B.8 Reduction of NOx vs. Costs for LIRS.

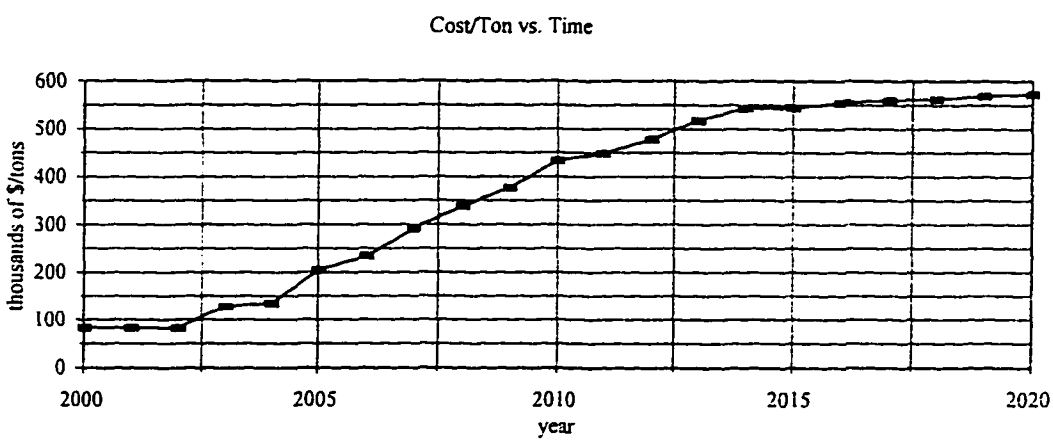


Figure B.9 Cost Efectiveness of NOx Reduction for LIRS.

Table B.4 Reduction of HC Emissions and Its Costs (MIRS).

| YEAR | MCEV | HC | | | Cost/ton |
|---|---|---|---|---|---|
| | (billions) | (thousands of tons) | | | thds.($) |
| | | No Action | MIRS | Reduction | per ton |
| 2000 | 1.590 | 151.02 | 139.82 | 11.198 | 142.012 |
| 2001 | 3.180 | 152.53 | 137.40 | 15.131 | 210.174 |
| 2002 | 4.770 | 154.06 | 134.30 | 19.754 | 241.469 |
| 2003 | 6.360 | 155.60 | 131.55 | 24.048 | 264.476 |
| 2004 | 7.951 | 157.15 | 128.34 | 28.810 | 275.982 |
| 2005 | 9.543 | 158.73 | 123.45 | 35.277 | 270.519 |
| 2006 | 11.136 | 160.31 | 117.57 | 42.739 | 260.565 |
| 2007 | 12.732 | 161.92 | 110.88 | 51.032 | 249.481 |
| 2008 | 14.330 | 163.53 | 104.54 | 58.996 | 242.893 |
| 2009 | 15.932 | 165.17 | 98.30 | 66.872 | 238.244 |
| 2010 | 17.539 | 166.82 | 91.86 | 74.958 | 233.986 |
| 2011 | 19.153 | 168.49 | 85.13 | 83.364 | 229.750 |
| 2012 | 20.774 | 170.17 | 78.46 | 91.713 | 226.507 |
| 2013 | 22.402 | 171.88 | 70.73 | 101.145 | 221.487 |
| 2014 | 24.040 | 173.60 | 64.52 | 109.080 | 220.385 |
| 2015 | 25.686 | 175.33 | 55.02 | 120.307 | 213.505 |
| 2016 | 27.343 | 177.08 | 47.15 | 129.938 | 210.427 |
| 2017 | 29.010 | 178.86 | 39.01 | 139.844 | 207.447 |
| 2018 | 30.689 | 180.64 | 31.44 | 149.200 | 205.693 |
| 2019 | 32.381 | 182.45 | 24.58 | 157.868 | 205.113 |
| 2020 | 34.084 | 184.28 | 17.72 | 166.551 | 204.646 |

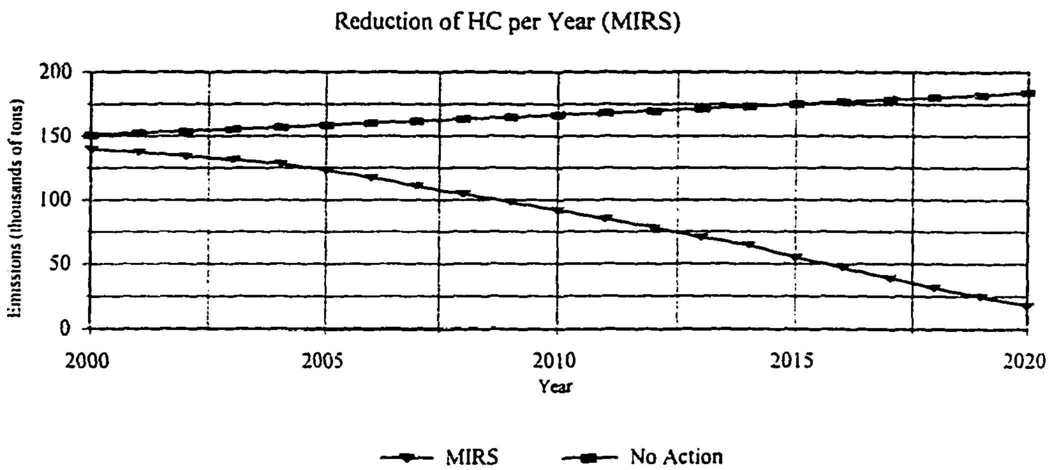


Figure B.10 Reduction of HC Emissions for MIRS.

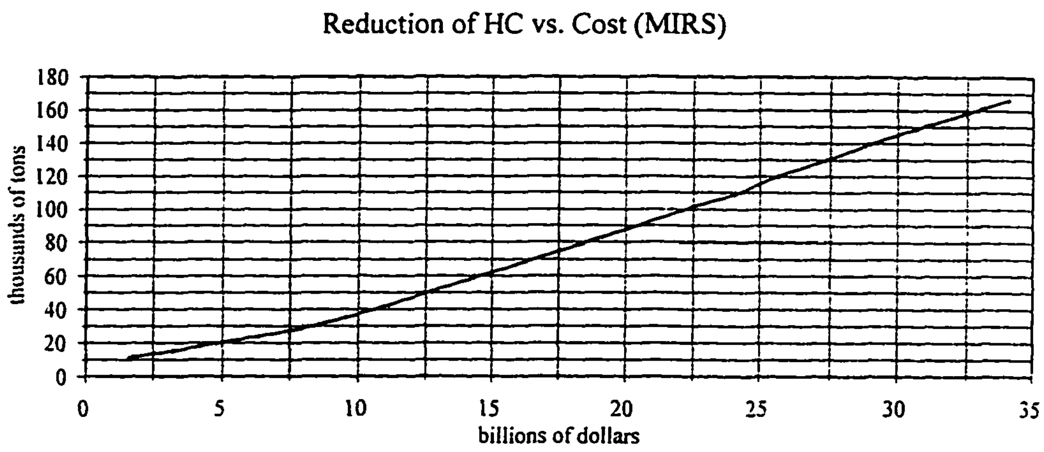


Figure B.11 Reduction of HC vs. Costs for MIRS.

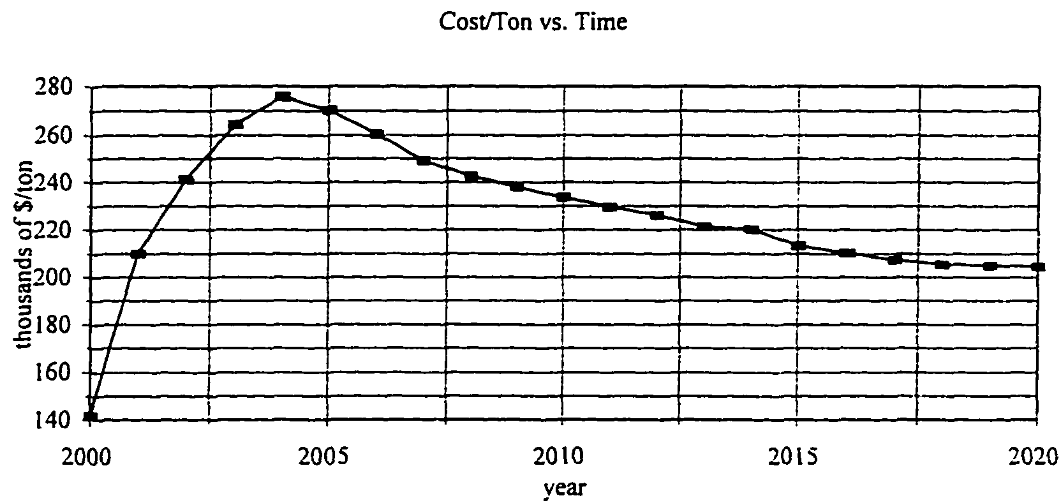


Figure B.12 Cost Efectiveness of HC Reduction for MIRS.

Table B.5 Reduction of CO Emissions and Its Costs (MIRS).

| YEAR | MCEV | CO | | | Cost/ton |
|---|---|---|---|---|---|
| | (billions) | (thousands of tons) | | | thds.($) |
| | | No Action | MIRS | Reduction | per ton |
| 2000 | 1.590 | 945.68 | 865.10 | 80.580 | 19.734 |
| 2001 | 3.180 | 955.13 | 876.08 | 79.055 | 40.227 |
| 2002 | 4.770 | 964.68 | 875.72 | 88.960 | 53.619 |
| 2003 | 6.360 | 974.33 | 869.52 | 104.809 | 60.682 |
| 2004 | 7.951 | 984.07 | 855.73 | 128.340 | 61.954 |
| 2005 | 9.543 | 993.92 | 826.66 | 167.257 | 57.056 |
| 2006 | 11.136 | 1003.85 | 788.86 | 214.993 | 51.799 |
| 2007 | 12.732 | 1013.89 | 744.97 | 268.921 | 47.343 |
| 2008 | 14.330 | 1024.03 | 704.65 | 319.386 | 44.867 |
| 2009 | 15.932 | 1034.27 | 664.48 | 369.787 | 43.084 |
| 2010 | 17.539 | 1044.61 | 622.32 | 422.292 | 41.533 |
| 2011 | 19.153 | 1055.06 | 580.10 | 474.965 | 40.325 |
| 2012 | 20.774 | 1065.61 | 537.97 | 527.637 | 39.371 |
| 2013 | 22.402 | 1076.27 | 484.43 | 591.834 | 37.852 |
| 2014 | 24.040 | 1087.03 | 435.90 | 651.135 | 36.919 |
| 2015 | 25.686 | 1097.90 | 380.37 | 717.533 | 35.798 |
| 2016 | 27.343 | 1108.88 | 323.99 | 784.890 | 34.836 |
| 2017 | 29.010 | 1119.97 | 260.67 | 859.300 | 33.760 |
| 2018 | 30.689 | 1131.17 | 202.12 | 929.047 | 33.033 |
| 2019 | 32.381 | 1142.48 | 162.63 | 979.854 | 33.047 |
| 2020 | 34.084 | 1153.90 | 117.79 | 1036.119 | 32.896 |

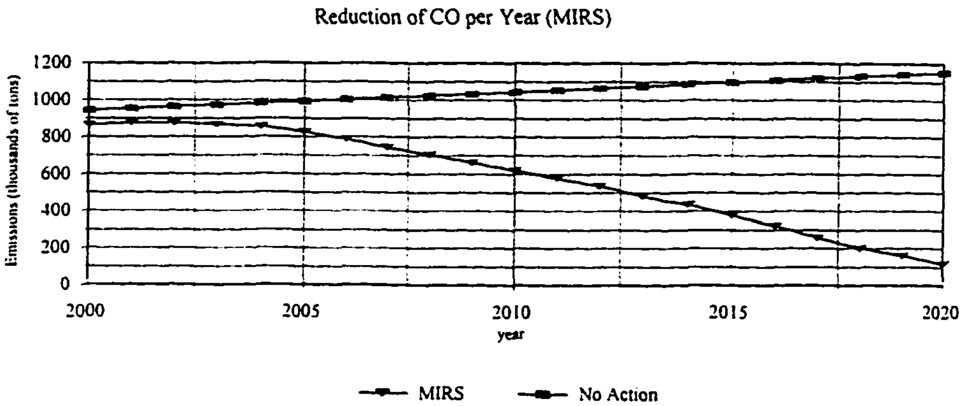


Figure B.13 Reduction of CO Emissions for MIRS.

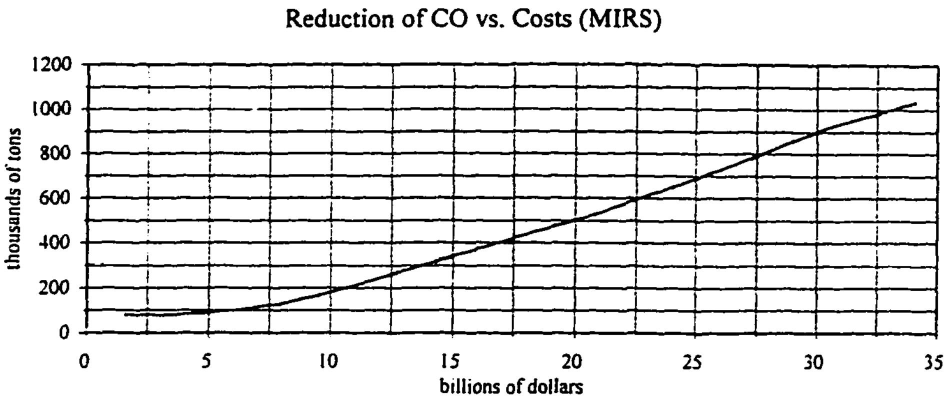


Figure B.14 Reduction of CO vs. Costs for MIRS.

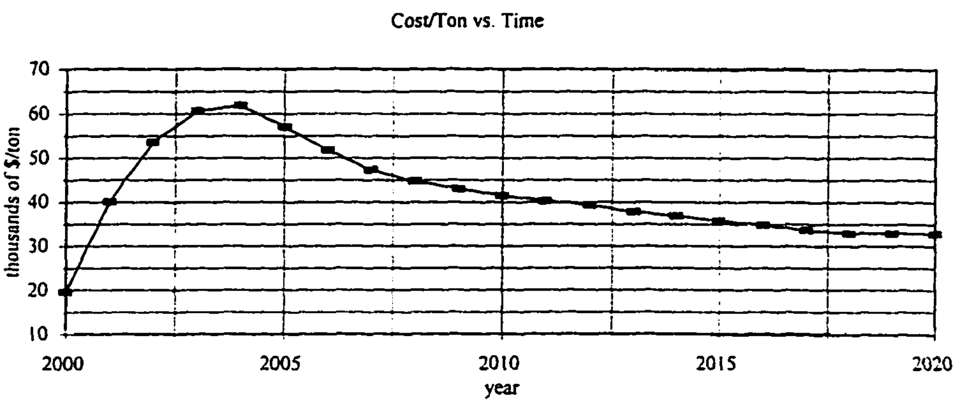


Figure B.15 Cost Efectiveness of CO Reduction for MIRS.

Table B.6 Reduction of NOx Emissions and Its Costs (MIRS).

| YEAR | MCEV | NOx | | | C$/Cton |
|---|---|---|---|---|---|
| | (billions) | (thousands of tons) | | | thds.($) |
| | | No Action | MIRS | Reduction | per ton |
| 2000 | 1.590 | 47.86 | 44.28 | 3.579 | 444.269 |
| 2001 | 3.180 | 48.34 | 43.92 | 4.414 | 720.432 |
| 2002 | 4.770 | 48.82 | 43.00 | 5.816 | 820.086 |
| 2003 | 6.360 | 49.31 | 41.63 | 7.675 | 828.680 |
| 2004 | 7.951 | 49.80 | 40.14 | 9.661 | 822.997 |
| 2005 | 9.543 | 50.30 | 38.22 | 12.074 | 790.398 |
| 2006 | 11.136 | 50.80 | 35.72 | 15.086 | 738.192 |
| 2007 | 12.732 | 51.31 | 32.80 | 18.509 | 687.844 |
| 2008 | 14.330 | 51.82 | 29.90 | 21.926 | 653.559 |
| 2009 | 15.932 | 52.34 | 26.80 | 25.540 | 623.806 |
| 2010 | 17.539 | 52.86 | 23.74 | 29.125 | 602.193 |
| 2011 | 19.153 | 53.39 | 20.68 | 32.714 | 585.459 |
| 2012 | 20.774 | 53.93 | 17.78 | 36.150 | 574.654 |
| 2013 | 22.402 | 54.47 | 14.72 | 39.748 | 563.616 |
| 2014 | 24.040 | 55.01 | 12.19 | 42.819 | 561.418 |
| 2015 | 25.686 | 55.56 | 9.93 | 45.635 | 562.855 |
| 2016 | 27.343 | 56.12 | 8.01 | 48.111 | 568.323 |
| 2017 | 29.010 | 56.68 | 6.43 | 50.249 | 577.329 |
| 2018 | 30.689 | 57.24 | 4.95 | 52.293 | 586.874 |
| 2019 | 32.381 | 57.82 | 3.42 | 54.400 | 595.232 |
| 2020 | 34.084 | 58.39 | 2.40 | 55.992 | 608.727 |

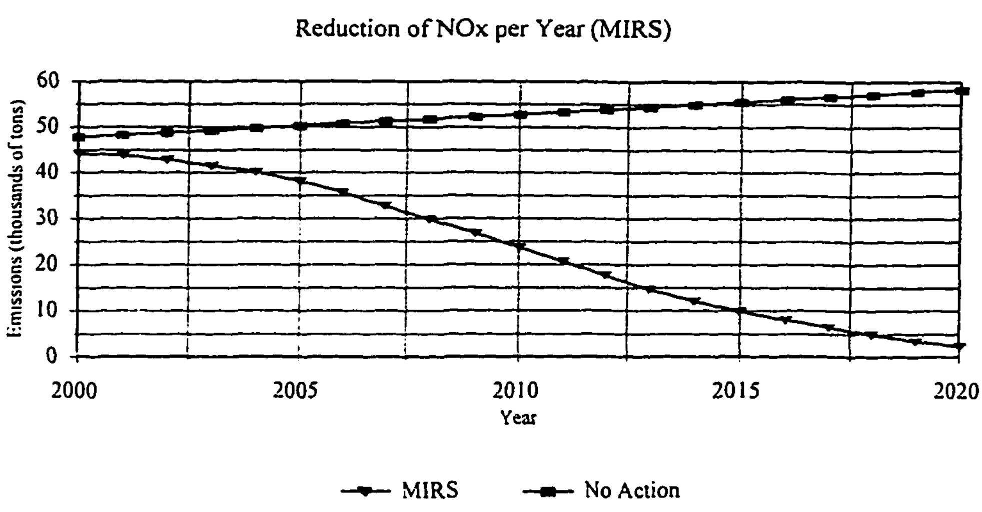


Figure B.16 Reduction of $NO_x$ Emissions for MIRS.

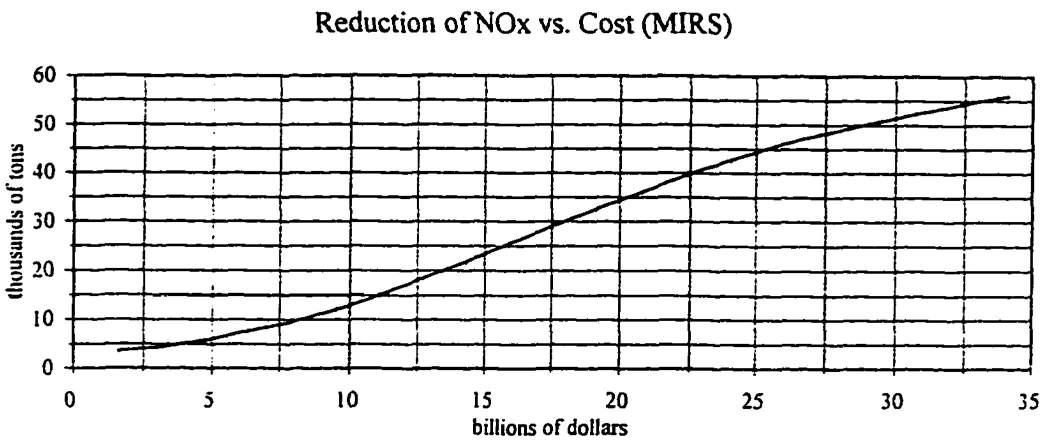


Figure B.17 Reduction of NOx vs. Costs for MIRS.

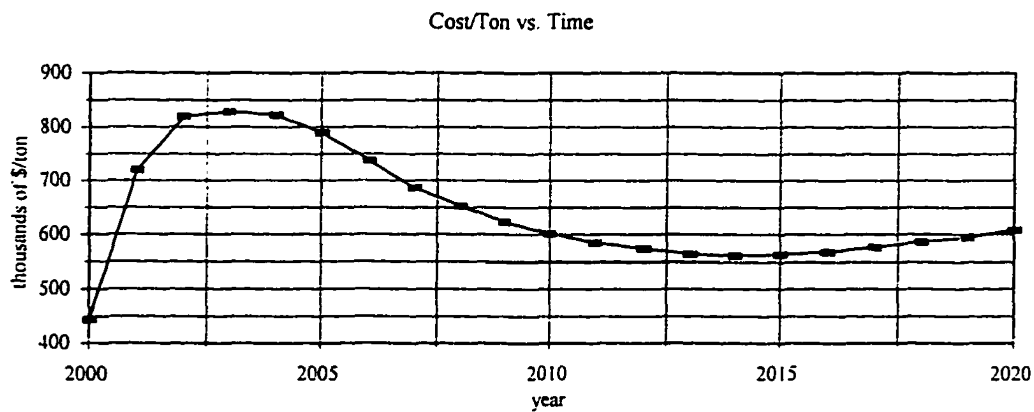


Figure B.18 Cost Efectivness of NOx Reduction for MIRS.

Table B.7 Reduction of HC Emissions and Its Costs (HIRS).

| YEAR | MCEV | HC | | | Cost/ton |
|---|---|---|---|---|---|
| | (billions) | (thousands of tons) | | | thds.($) |
| | | No Action | HIRS | Reduction | per ton |
| 2000 | 1.655 | 151.02 | 138.70 | 12.326 | 134.308 |
| 2001 | 3.352 | 152.53 | 133.59 | 18.944 | 176.917 |
| 2002 | 5.084 | 154.06 | 127.41 | 26.646 | 190.782 |
| 2003 | 6.847 | 155.60 | 119.89 | 35.706 | 191.773 |
| 2004 | 8.636 | 157.15 | 111.53 | 45.627 | 189.285 |
| 2005 | 10.491 | 158.73 | 100.31 | 58.416 | 179.590 |
| 2006 | 12.380 | 160.31 | 87.10 | 73.208 | 169.104 |
| 2007 | 14.317 | 161.92 | 72.18 | 89.734 | 159.552 |
| 2008 | 16.321 | 163.53 | 56.94 | 106.596 | 153.107 |
| 2009 | 18.435 | 165.17 | 40.97 | 124.198 | 148.430 |
| 2010 | 20.147 | 166.82 | 33.10 | 133.719 | 150.665 |
| 2011 | 21.879 | 168.49 | 25.20 | 143.287 | 152.692 |
| 2012 | 23.627 | 170.17 | 17.28 | 152.895 | 154.528 |
| 2013 | 25.386 | 171.88 | 8.51 | 163.370 | 155.390 |
| 2014 | 27.177 | 173.60 | 0.00 | 173.595 | 156.554 |
| 2015 | 28.550 | 175.33 | 0.00 | 175.331 | 162.835 |
| 2016 | 30.016 | 177.08 | 0.00 | 177.085 | 169.501 |
| 2017 | 31.531 | 178.86 | 0.00 | 178.856 | 176.295 |
| 2018 | 33.066 | 180.64 | 0.00 | 180.644 | 183.044 |
| 2019 | 34.628 | 182.45 | 0.00 | 182.451 | 189.795 |
| 2020 | 36.237 | 184.28 | 0.00 | 184.275 | 196.644 |

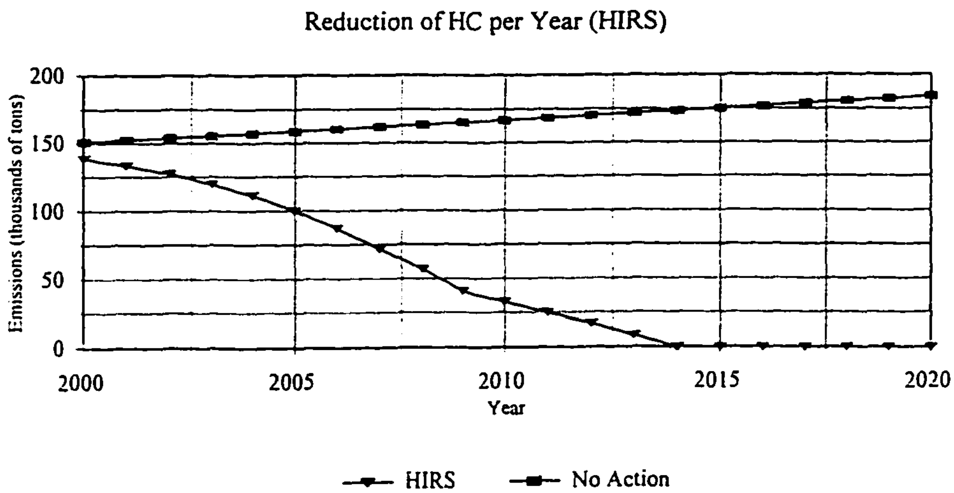


Figure B.19 Reduction of HC Emissions for HIRS.

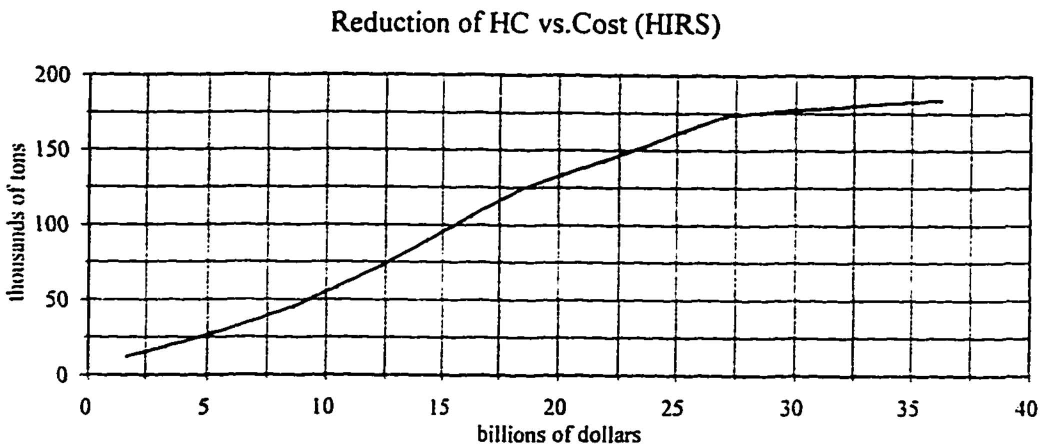


Figure B.20 Reduction of HC vs. Costs for HIRS.

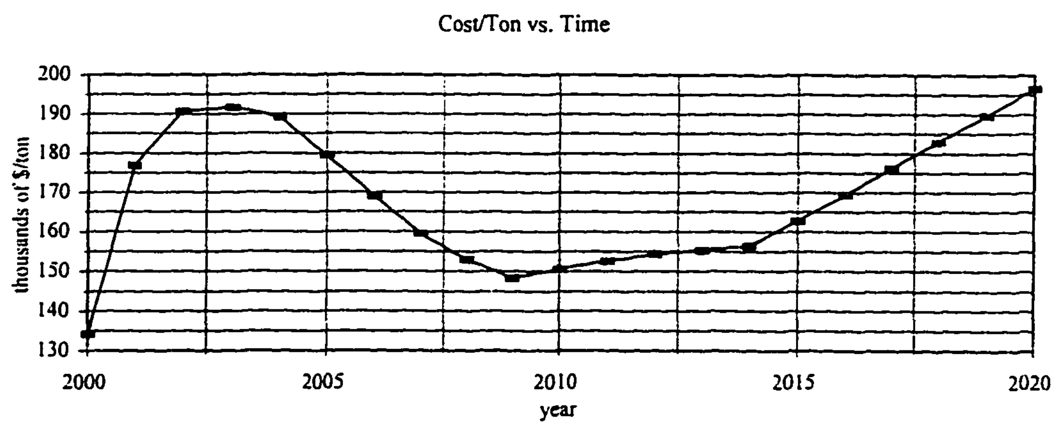


Figure B.21 Costs Efectiveness of HC Reduction for HIRS.

Table B.8 Reduction of CO Emissions and Its Costs (HIRS).

| YEAR | MCEV | CO | | | Cost/ton |
|---|---|---|---|---|---|
| | (billions) | (thousands of tons) | | | thds.($) |
| | | No Action | HIRS | Reduction | per ton |
| 2000 | 1.655 | 945.68 | 857.44 | 88.239 | 18.762 |
| 2001 | 3.352 | 955.13 | 852.32 | 102.818 | 32.597 |
| 2002 | 5.084 | 964.68 | 829.72 | 134.965 | 37.666 |
| 2003 | 6.847 | 974.33 | 792.85 | 181.482 | 37.731 |
| 2004 | 8.636 | 984.07 | 744.35 | 239.723 | 36.027 |
| 2005 | 10.491 | 993.92 | 676.19 | 317.726 | 33.019 |
| 2006 | 12.380 | 1003.85 | 584.81 | 419.040 | 29.543 |
| 2007 | 14.317 | 1013.89 | 480.39 | 533.507 | 26.836 |
| 2008 | 16.321 | 1024.03 | 377.42 | 646.609 | 25.240 |
| 2009 | 18.435 | 1034.27 | 269.23 | 765.043 | 24.096 |
| 2010 | 20.147 | 1044.61 | 217.46 | 827.155 | 24.357 |
| 2011 | 21.879 | 1055.06 | 166.50 | 888.563 | 24.623 |
| 2012 | 23.627 | 1065.61 | 115.12 | 950.494 | 24.857 |
| 2013 | 25.386 | 1076.27 | 54.57 | 1021.698 | 24.847 |
| 2014 | 27.177 | 1087.03 | 0.00 | 1087.031 | 25.001 |
| 2015 | 28.550 | 1097.90 | 0.00 | 1097.901 | 26.004 |
| 2016 | 30.016 | 1108.88 | 0.00 | 1108.880 | 27.069 |
| 2017 | 31.531 | 1119.97 | 0.00 | 1119.969 | 28.154 |
| 2018 | 33.066 | 1131.17 | 0.00 | 1131.168 | 29.232 |
| 2019 | 34.628 | 1142.48 | 0.00 | 1142.480 | 30.310 |
| 2020 | 36.237 | 1153.90 | 0.00 | 1153.905 | 31.403 |

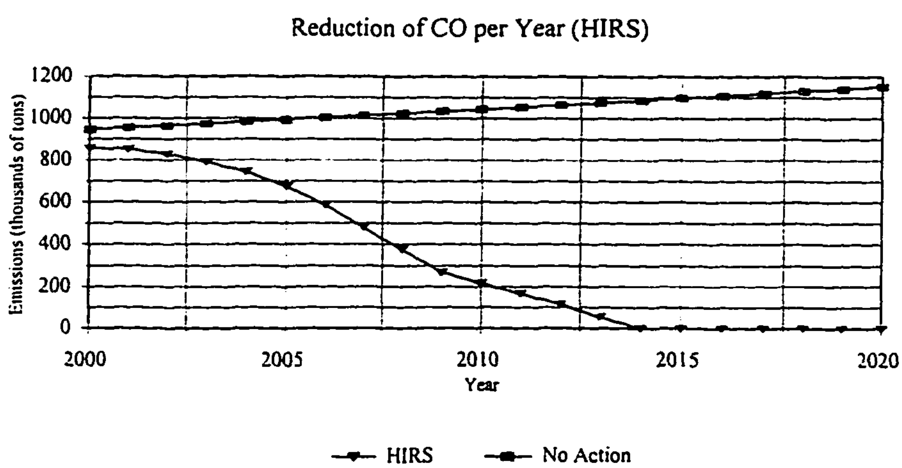


Figure B. 22 Reduction of CO Emissions for HIRS.

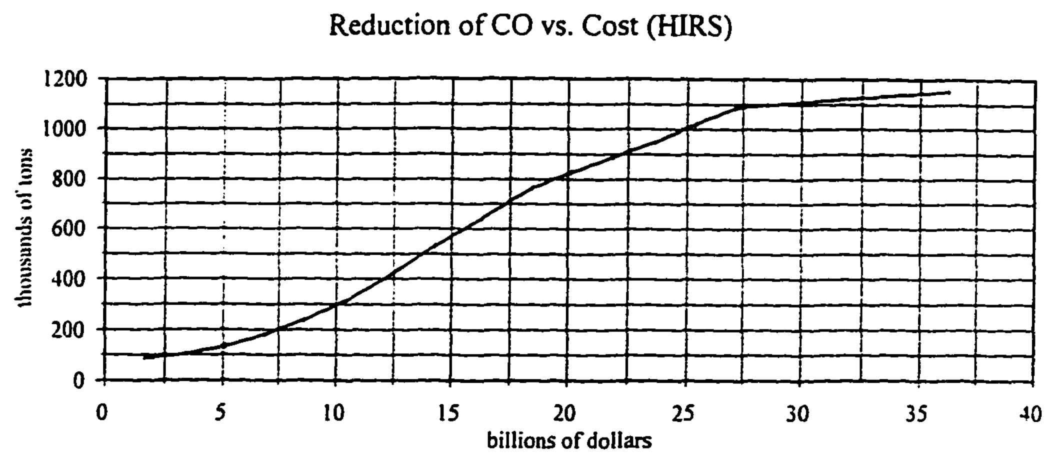


Figure B.23 Reduction of CO vs. Costs for HIRS.

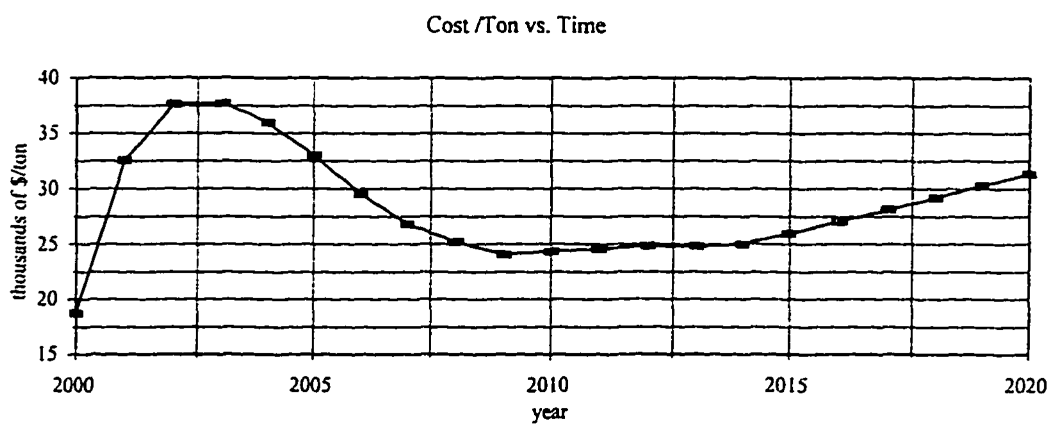


Figure B.24 Cost Efectiveness of CO Reduction for HIRS.

Table B.9 Reduction of NOx Emissions and Its Costs (HIRS).

| YEAR | MCEV | NOx | | | Cost/ton |
|---|---|---|---|---|---|
| | (billions) | (thousands of tons) | | | thds.($) |
| | | No Action | HIRS | Reduction | per ton |
| 2000 | 1.655 | 47.86 | 44.08 | 3.773 | 438.725 |
| 2001 | 3.352 | 48.34 | 43.14 | 5.198 | 644.794 |
| 2002 | 5.084 | 48.82 | 41.71 | 7.106 | 715.425 |
| 2003 | 6.847 | 49.31 | 39.66 | 9.646 | 709.845 |
| 2004 | 8.636 | 49.80 | 37.12 | 12.677 | 681.276 |
| 2005 | 10.491 | 50.30 | 33.70 | 16.595 | 632.162 |
| 2006 | 12.380 | 50.80 | 29.66 | 21.141 | 585.566 |
| 2007 | 14.317 | 51.31 | 25.15 | 26.160 | 547.289 |
| 2008 | 16.321 | 51.82 | 20.13 | 31.690 | 515.004 |
| 2009 | 18.435 | 52.34 | 14.66 | 37.680 | 489.240 |
| 2010 | 20.147 | 52.86 | 11.55 | 41.316 | 487.623 |
| 2011 | 21.879 | 53.39 | 8.49 | 44.903 | 487.245 |
| 2012 | 23.627 | 53.93 | 5.53 | 48.394 | 488.219 |
| 2013 | 25.386 | 54.47 | 2.53 | 51.941 | 488.753 |
| 2014 | 27.177 | 55.01 | 0.00 | 55.010 | 494.035 |
| 2015 | 28.550 | 55.56 | 0.00 | 55.560 | 513.855 |
| 2016 | 30.016 | 56.12 | 0.00 | 56.116 | 534.891 |
| 2017 | 31.531 | 56.68 | 0.00 | 56.677 | 556.333 |
| 2018 | 33.066 | 57.24 | 0.00 | 57.244 | 577.629 |
| 2019 | 34.628 | 57.82 | 0.00 | 57.816 | 598.932 |
| 2020 | 36.237 | 58.39 | 0.00 | 58.395 | 620.547 |

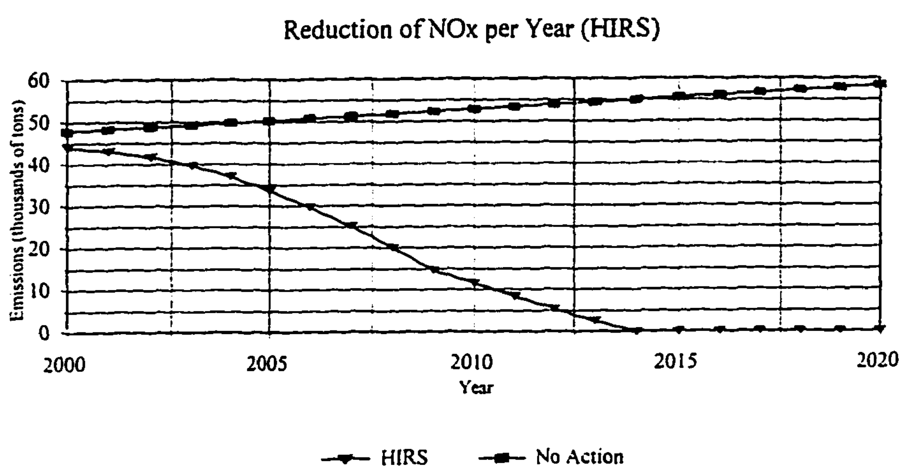


Figure B.25 Reduction of NOx Emissions for HIRS.

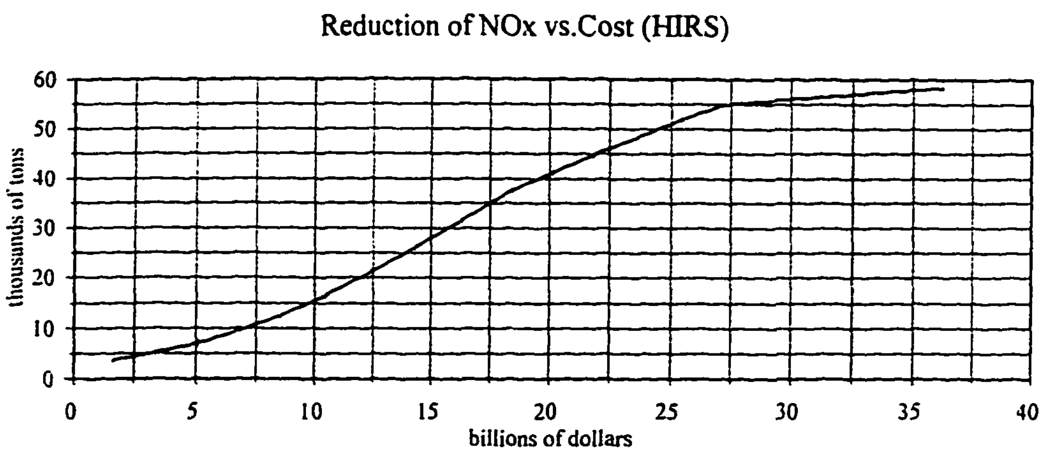


Figure B.26 Reduction of NOx vs. Costs for HIRS.

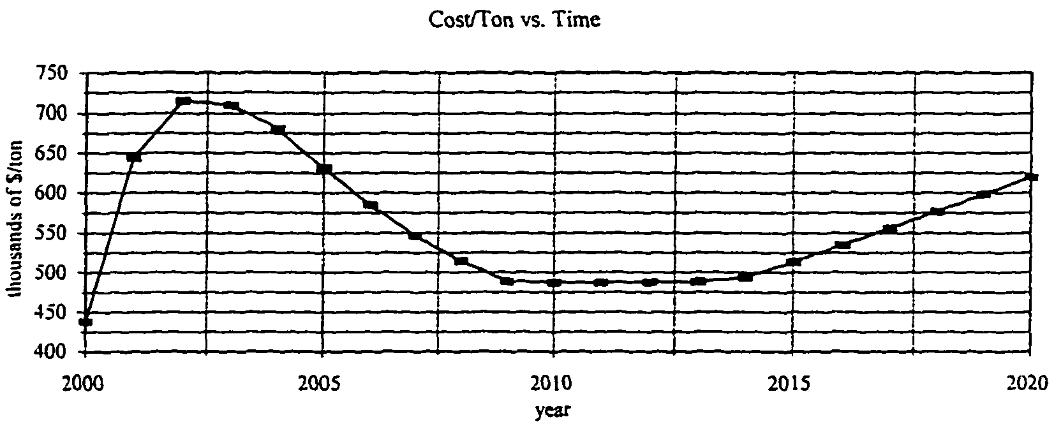


Figure B.27 Cost Efectiveness of NOx Reduction for HIRS.

Table B.10 Reduction of HC Emissions and Its Costs (FRTS).

| YEAR | MCEV | HC | | | Cost/ton |
|---|---|---|---|---|---|
| | (billions) | (thousands of tons) | | | thds.($) |
| | | No Action | FRTS | Reduction | per ton |
| 2000 | 0.107 | 151.02 | 149.88 | 1.146 | 93.322 |
| 2001 | 0.385 | 152.53 | 148.48 | 4.052 | 95.038 |
| 2002 | 0.781 | 154.06 | 147.04 | 7.016 | 111.304 |
| 2003 | 1.273 | 155.60 | 144.08 | 11.515 | 110.551 |
| 2004 | 1.840 | 157.15 | 141.65 | 15.507 | 118.654 |
| 2005 | 2.533 | 158.73 | 139.45 | 19.276 | 131.385 |
| 2006 | 3.356 | 160.31 | 136.89 | 23.423 | 143.288 |
| 2007 | 4.274 | 161.92 | 134.26 | 27.652 | 154.550 |
| 2008 | 5.322 | 163.53 | 132.19 | 31.342 | 169.804 |
| 2009 | 6.590 | 165.17 | 129.44 | 35.729 | 184.430 |
| 2010 | 7.296 | 166.82 | 131.37 | 35.454 | 205.779 |
| 2011 | 8.002 | 168.49 | 134.28 | 34.210 | 233.900 |
| 2012 | 8.708 | 170.17 | 136.59 | 33.583 | 259.288 |
| 2013 | 9.414 | 171.88 | 139.59 | 32.288 | 291.554 |
| 2014 | 10.120 | 173.60 | 142.96 | 30.634 | 330.338 |
| 2015 | 10.939 | 175.33 | 144.72 | 30.608 | 357.384 |
| 2016 | 11.782 | 177.08 | 146.17 | 30.914 | 381.104 |
| 2017 | 12.647 | 178.86 | 147.63 | 31.223 | 405.035 |
| 2018 | 13.533 | 180.64 | 148.77 | 31.878 | 424.517 |
| 2019 | 14.434 | 182.45 | 149.91 | 32.543 | 443.527 |
| 2020 | 15.374 | 184.28 | 151.41 | 32.869 | 467.729 |

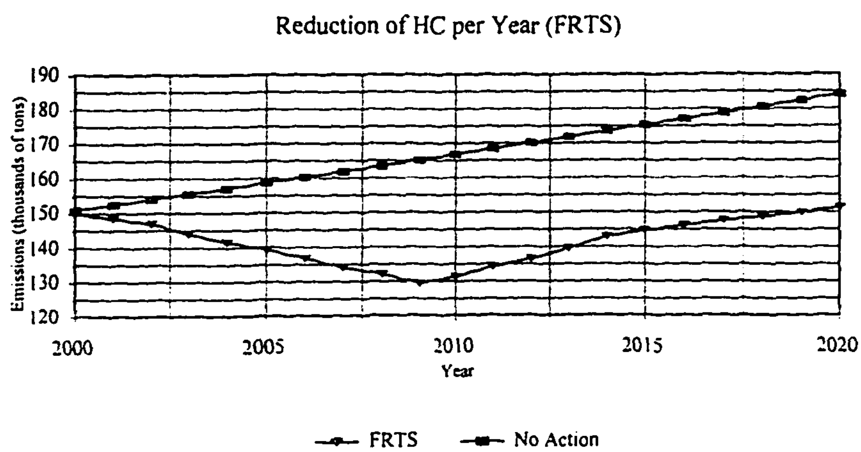


Figure B.28 Reduction of HC Emissions for FRTS.

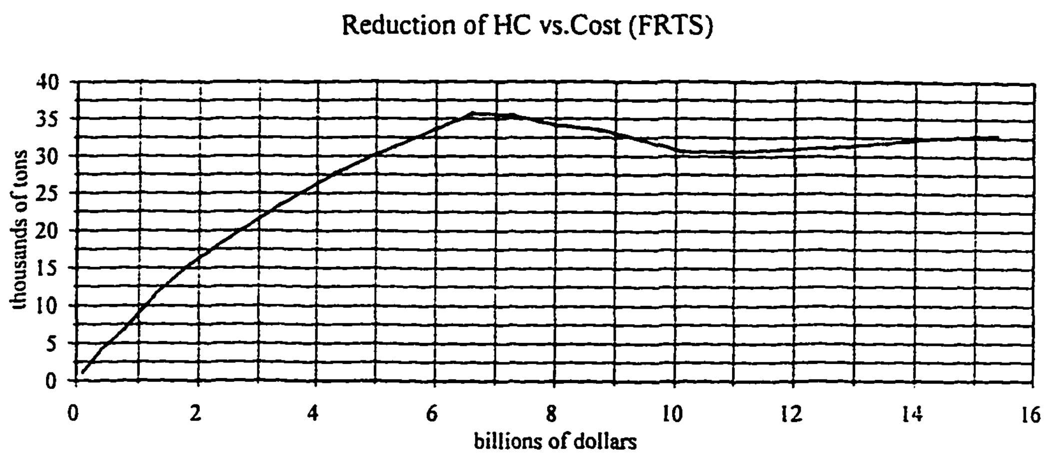


Figure B.29 Reduction of HC vs. Costs for FRTS.

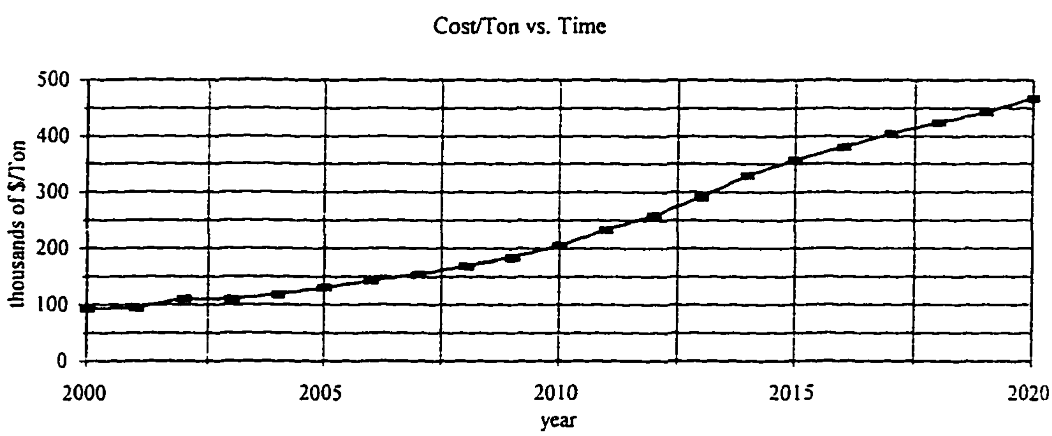


Figure B.30 Cost Efectiveness of HC Reduction for FRTS.

Table B.11 Reduction of CO Emissions and Its Costs (FRTS).

| YEAR | MCEV | CO | | | Cost/ton |
|---|---|---|---|---|---|
| | (billions) | (thousands of tons) | | | thds.($) |
| | | No Action | FRTS | Reduction | per ton |
| 2000 | 0.107 | 945.68 | 913.29 | 32.382 | 3.303 |
| 2001 | 0.385 | 955.13 | 899.56 | 55.571 | 6.930 |
| 2002 | 0.781 | 964.68 | 884.59 | 80.098 | 9.749 |
| 2003 | 1.273 | 974.33 | 861.84 | 112.491 | 11.316 |
| 2004 | 1.840 | 984.07 | 843.62 | 140.454 | 13.100 |
| 2005 | 2.533 | 993.92 | 830.37 | 163.544 | 15.486 |
| 2006 | 3.356 | 1003.85 | 807.95 | 195.904 | 17.132 |
| 2007 | 4.274 | 1013.89 | 783.16 | 230.737 | 18.521 |
| 2008 | 5.322 | 1024.03 | 764.61 | 259.421 | 20.515 |
| 2009 | 6.590 | 1034.27 | 741.54 | 292.730 | 22.511 |
| 2010 | 7.296 | 1044.61 | 754.34 | 290.276 | 25.133 |
| 2011 | 8.002 | 1055.06 | 777.23 | 277.833 | 28.800 |
| 2012 | 8.708 | 1065.61 | 808.90 | 256.716 | 33.919 |
| 2013 | 9.414 | 1076.27 | 816.98 | 259.283 | 36.307 |
| 2014 | 10.120 | 1087.03 | 836.68 | 250.346 | 40.423 |
| 2015 | 10.939 | 1097.90 | 847.71 | 250.188 | 43.722 |
| 2016 | 11.782 | 1108.88 | 854.85 | 254.034 | 46.378 |
| 2017 | 12.647 | 1119.97 | 860.00 | 259.968 | 48.646 |
| 2018 | 13.533 | 1131.17 | 866.54 | 264.625 | 51.140 |
| 2019 | 14.434 | 1142.48 | 873.82 | 268.656 | 53.726 |
| 2020 | 15.374 | 1153.90 | 881.16 | 272.741 | 56.367 |

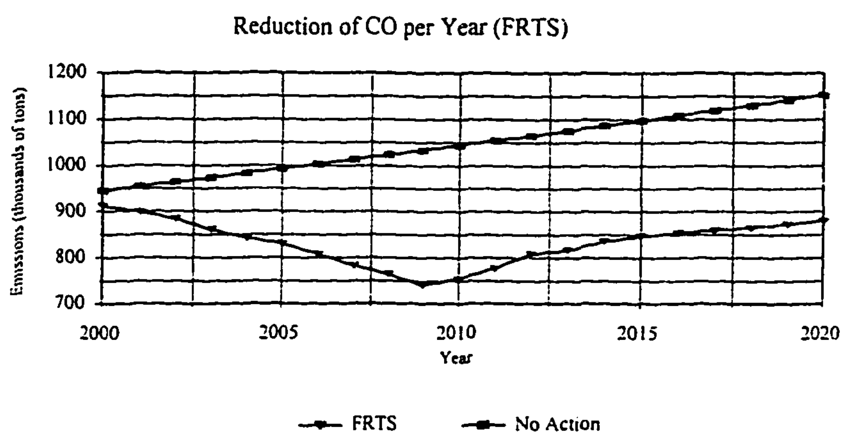


Figure B.31 Reduction of CO Emissions for FRTS.

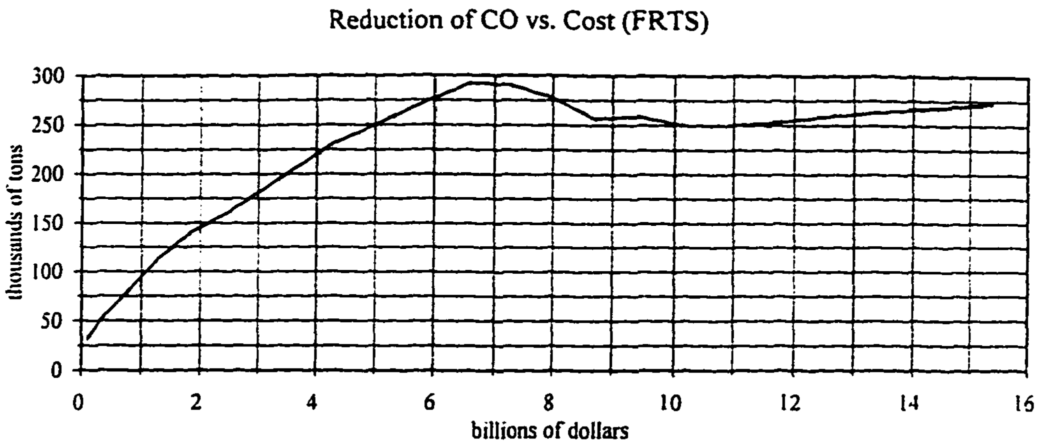


Figure B.32 Reduction of CO vs. Costs for FRTS.

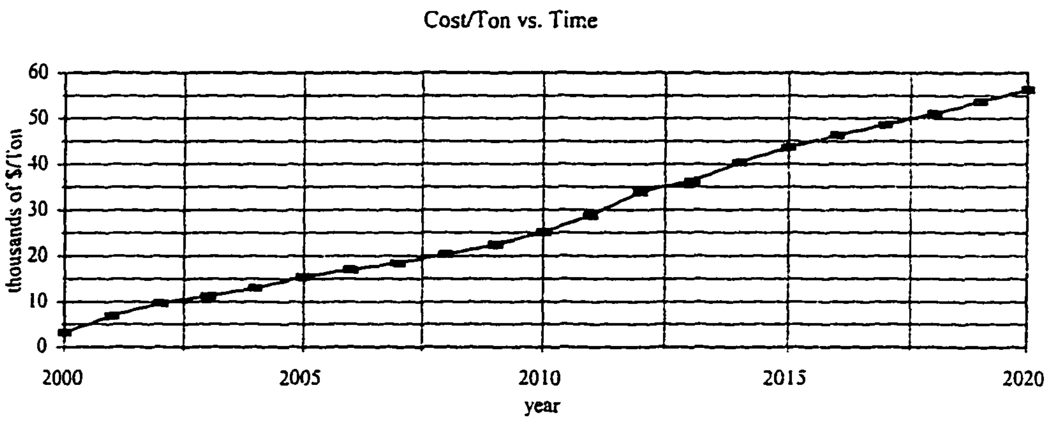


Figure B.33 Cost Efectiveness of CO Reduction for FRTS.

Table B.12 Reduction of NOx Emissions and Its Costs (FRTS).

| YEAR | MCEV | NOx | | | Cost/ton |
|---|---|---|---|---|---|
| | (billions) | (thousands of tons) | | | thds.($) |
| | | No Action | FRTS | Reduction | per ton |
| 2000 | 0.107 | 47.86 | 47.57 | 0.287 | 373.289 |
| 2001 | 0.385 | 48.34 | 47.18 | 1.158 | 332.632 |
| 2002 | 0.781 | 48.82 | 47.06 | 1.754 | 445.217 |
| 2003 | 1.273 | 49.31 | 46.95 | 2.362 | 538.934 |
| 2004 | 1.840 | 49.80 | 46.82 | 2.982 | 617.002 |
| 2005 | 2.533 | 50.30 | 46.38 | 3.915 | 646.821 |
| 2006 | 3.356 | 50.80 | 46.24 | 4.563 | 735.545 |
| 2007 | 4.274 | 51.31 | 46.09 | 5.223 | 818.208 |
| 2008 | 5.322 | 51.82 | 45.93 | 5.896 | 902.640 |
| 2009 | 6.590 | 52.34 | 45.45 | 6.895 | 955.680 |
| 2010 | 7.296 | 52.86 | 45.90 | 6.964 | 1047.600 |
| 2011 | 8.002 | 53.39 | 47.32 | 6.075 | 1317.227 |
| 2012 | 8.708 | 53.93 | 48.76 | 5.167 | 1685.374 |
| 2013 | 9.414 | 54.47 | 49.25 | 5.218 | 1803.988 |
| 2014 | 10.120 | 55.01 | 50.40 | 4.612 | 2194.386 |
| 2015 | 10.939 | 55.56 | 51.24 | 4.325 | 2529.177 |
| 2016 | 11.782 | 56.12 | 51.75 | 4.368 | 2697.042 |
| 2017 | 12.647 | 56.68 | 51.93 | 4.751 | 2661.657 |
| 2018 | 13.533 | 57.24 | 52.45 | 4.799 | 2820.003 |
| 2019 | 14.434 | 57.82 | 52.97 | 4.847 | 2977.967 |
| 2020 | 15.374 | 58.39 | 53.15 | 5.245 | 2931.101 |

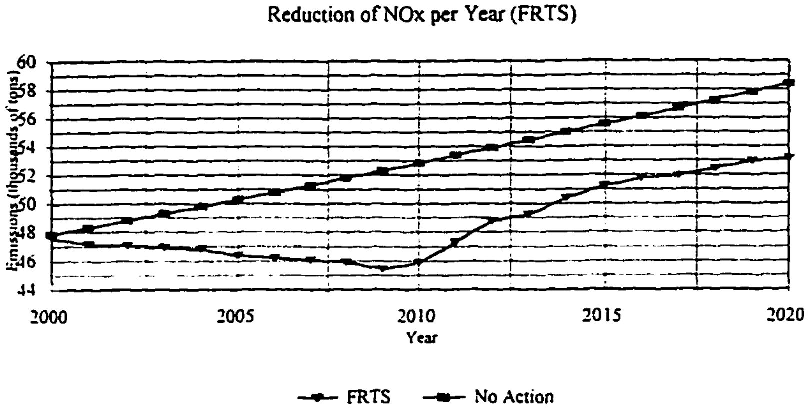


Figure B.34 Reduction of NOx Emissions for FRTS.

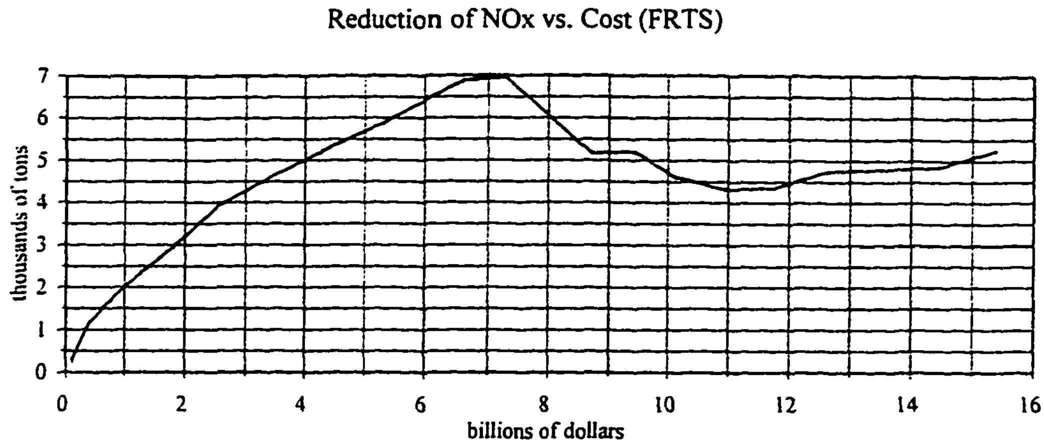


Figure B.35 Reduction of NOx vs. Costs for FRTS.

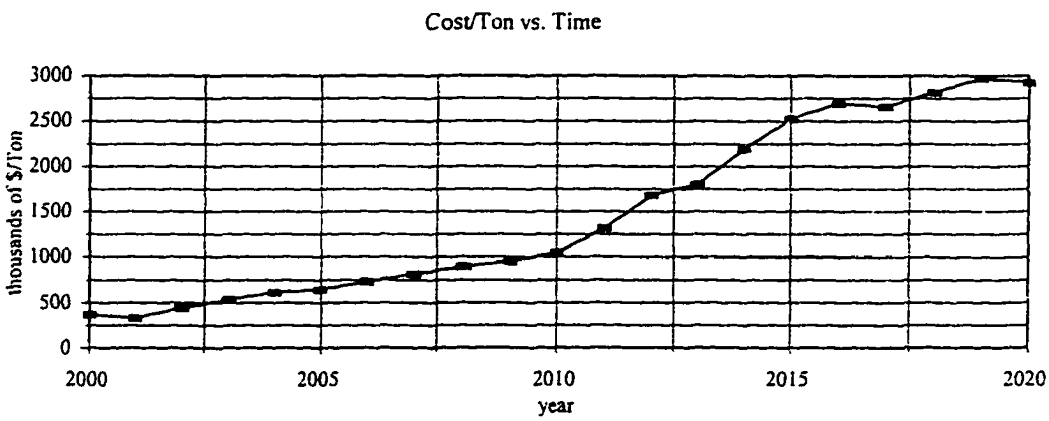


Figure B.36 Cost Effectiveness of NOx Reduction for FRTS.

# VITA

Hector David Arias-Varela was born in Tijuana, Baja California, Mexico on November 12, 1966. He received his bachelor of science degree in Electrical and Mechanical Engineering in 1989 from the Institute of Technology of Tijuana, Baja California, Mexico. In 1992 he obtained his master of science degree in Mechanical Engineering from the National Center of Research and Technological Development in Cuernavaca, Morelos, Mexico. For his thesis he designed a solar refrigerator to preserve seafood in rural areas. From 1991 to 1992 he worked as a researcher in the Laboratory of Solar Energy of the "Universidad Nacional Autonoma de Mexico" (UNAM). In 1993, he taught as an associate professor in the Institute of Technology of Tijuana. In the Summer of 1993, he was nominated as a Fulbright Scholar and was granted a scholarship to study for his Doctor of Philosophy degree at Louisiana State University (LSU). He joined the College of Engineering Science and the Department of Industrial and Manufacturing Systems Engineering of LSU in the Fall of 1993. In 1994, Hector was married to Julie Jacobson in Baton Rouge, Louisiana, where his daughter, Rebeca Aurora, was born in February 24, 1996. Hector enjoyed working on his dissertation project under the supervision of his major professor Dr. Gerald M. Knapp and his Graduate Committee.

## DOCTORAL EXAMINATION AND DISSERTATION REPORT

**Candidate:** Hector David Arias-Varela

**Major Field:** Engineering Science

**Title of Dissertation:** Cost Analysis and Air Pollution Impact of Electric Vehicles on a Metropolitan Area

**Approved:**

Major Professor and Chairman

Dean of the Graduate School

**EXAMINING COMMITTEE:**

Marty E. Tittlebaum

**Date of Examination:**